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216-Z-12 Transuranic Crib Characterization: Operational History and Distribution of Plutonium and Americium

R.B. Kasper

Prepared for the United States
Department of Energy
Under Contract DE-AC06-77RL01030

Rockwell International

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Health, Safety and Environment

November 1982

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ABSTRACT

Past radioactive liquid waste disposal practices at the Hanford Site included the discharge of process waste solutions containing low-level concentrations of plutonium directly to the ground via underground structures collectively termed "cribs." The spatial distribution of plutonium and americium beneath the retired 216-Z-12 Crib has been studied. The 216-Z-12 Crib received "low-salt" aqueous waste from 1959 to 1973, when the crib was retired from service. The crib received 2.8×10^8 L of aqueous waste containing 25.1 kg of plutonium. Americium activity was determined to be derived from the in situ decay of ^{241}Pu, not from a separate waste source. No other transuranic elements were discharged to the crib in any significant amounts.

Wells were drilled in and around the crib using specialized techniques for obtaining radioactively contaminated sediment samples. Samples from each well were analyzed to determine sediment type, moisture content, and plutonium and americium concentrations.

Study results show that plutonium concentration is highest (on the order of 1 to 5 million pCi/g of sediment) in the sediment immediately beneath the crib bottom. Plutonium concentrations decrease rapidly with distance from the bottom of the crib. Three meters below the crib, plutonium activity is less than 1,000 pCi/g and 10 m below the crib, activity is less than 1 pCi/g. Plutonium activity increases to a few tens of picocuries per gram 30 to 36 m beneath the crib bottom. The activity is associated with a silt unit at that depth and is probably related to the silt unit's greater sorption capacity. Results from ground-water monitoring beneath the 216-Z-12 Crib indicate measurable concentrations of plutonium did not break through to the ground water.

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SUMMARY

The distribution of plutonium and americium beneath the 216-Z-12 Crib was studied. The 216-Z-12 Crib design was typical for an aqueous waste crib. The 216-Z-12 Crib received a plutonium-bearing liquid waste from laboratories and process operations in Z Plant from 1959 to 1973. The waste was classified as "low-salt" aqueous waste and consisted primarily of a dilute (∿0.1M), slightly basic (pH ∿8), sodium, fluoride, and nitrate solution. The crib received 2.8×10^8 L of aqueous waste containing a reported 25.1 kg of plutonium.

Plutonium and americium distributions were determined by analyzing sediment samples from wells in and around the crib. Specialized techniques and procedures were used to obtain radioactively contaminated sediment samples. Sediment type, moisture content, and plutonium and americium concentrations were determined. Acquired data were used to construct cross sections to illustrate the distribution of plutonium and americium and the geology beneath the crib.

Conclusions concerning the distribution of plutonium and americium at the 216-Z-12 Crib are listed below.

- The highest concentration of plutonium is found in the sediments immediately below the crib bottom. Activity decreases rapidly with distance from the crib bottom. Plutonium activity is less than 1,000 pCi/g, 3 m below the crib and generally less than 1 pCi/g, 10 m below the crib.
- The distributions of plutonium and americium activity are similar. The ratio of americium to plutonium activity suggests that the americium is derived from the in situ decay of ^{241}Pu discharged in the waste, not from a separate waste source of americium.
- A low level of plutonium and americium activity occurs from 30 to 36 m below the crib bottom, the maximum depth sampled. Activity ranges from a few to a few tens of picocuries per gram for plutonium. The levels of activity are below limits

at the Hanford Site for surface soil contamination. The increase in activity is associated with a massive silt unit; the greater sorption capacity of silt-sized particles compared with the surrounding sand and gravel units probably concentrated most of the plutonium remaining in solution in the silt unit.

- Routine ground-water monitoring at the 216-Z-12 Crib indicates the concentration of alpha-emitting radionuclides has remained below the instrumental detection limit of 1.7×10^{-2} pCi/mL. Considering the ground-water monitoring data and the low levels of activity detected in the silt unit, the results indicate almost all the plutonium was sorbed within a few meters of the crib bottom, and measurable concentrations of plutonium did not break through to the ground water.
- A 1967 study of the 216-Z-12 Crib indicated the crib design did not effectively distribute the waste liquid over the entire bottom area of the crib. The current study supports that observation. Even after the diversion of the waste line to bypass the northern third of the crib, which had received waste, liquid waste still did not reach the southern third of the crib. In addition, the pipe connecting the diversion box to the perforated distributor pipe leaked and caused a thin layer of plutonium contamination between the crib and the diversion box. Levels of plutonium activity detected were comparable to those found in the crib.

INTRODUCTION

The U.S. Department of Energy's (DOE) Hanford Site is located in southeastern Washington State near the confluence of the Columbia and Snake Rivers (Figure 1). The Hanford Site was selected during the Manhattan Project as the location of nuclear reactors and chemical separation facilities for the production of plutonium (Figure 2). Chemical purification processes produced plutonium-bearing liquid waste.

Before 1973, chemical process waste solutions with low concentrations of plutonium were discharged directly to the unsaturated sediments beneath Hanford's 200 East and 200 West Areas. This liquid waste disposal practice is possible because waste-sediment interactions can remove radionuclides from the liquid phase, retaining them on the sediment near the point of release. However, the long half-life of plutonium (24,110 yr) may make near-surface storage in the sediments beneath the retired underground liquid waste sites only a temporary solution. Various options for the ultimate disposal of the contaminated sediments are being studied. To provide the needed input, field studies of individual retired liquid waste disposal sites are conducted to define the distribution of plutonium and other transuranic radionuclides beneath the sites. The data obtained also allow comparison of the predicted behavior of plutonium and other transuranic radionuclides with their actual behavior in the field.

Radioactive wastes have been discharged to the ground via a variety of underground structures that include cribs, French drains, and reverse wells. Official waste discharge records indicate approximately 200 kg of plutonium has been discharged to the ground in liquid waste and more than 90% (~182 kg) of that waste was released to cribs (Manry, 1979). Of the cribs that received plutonium-bearing liquid wastes, more than 80% (155.7 kg) of the plutonium inventory is in the six cribs reported in Table 1. All these cribs received waste from Z Plant in 200 West Area. The Z Plant complex was the site of the plutonium laboratory and finishing operations, including recovery of plutonium from scrap materials and preparation of plutonium products (Figure 3).

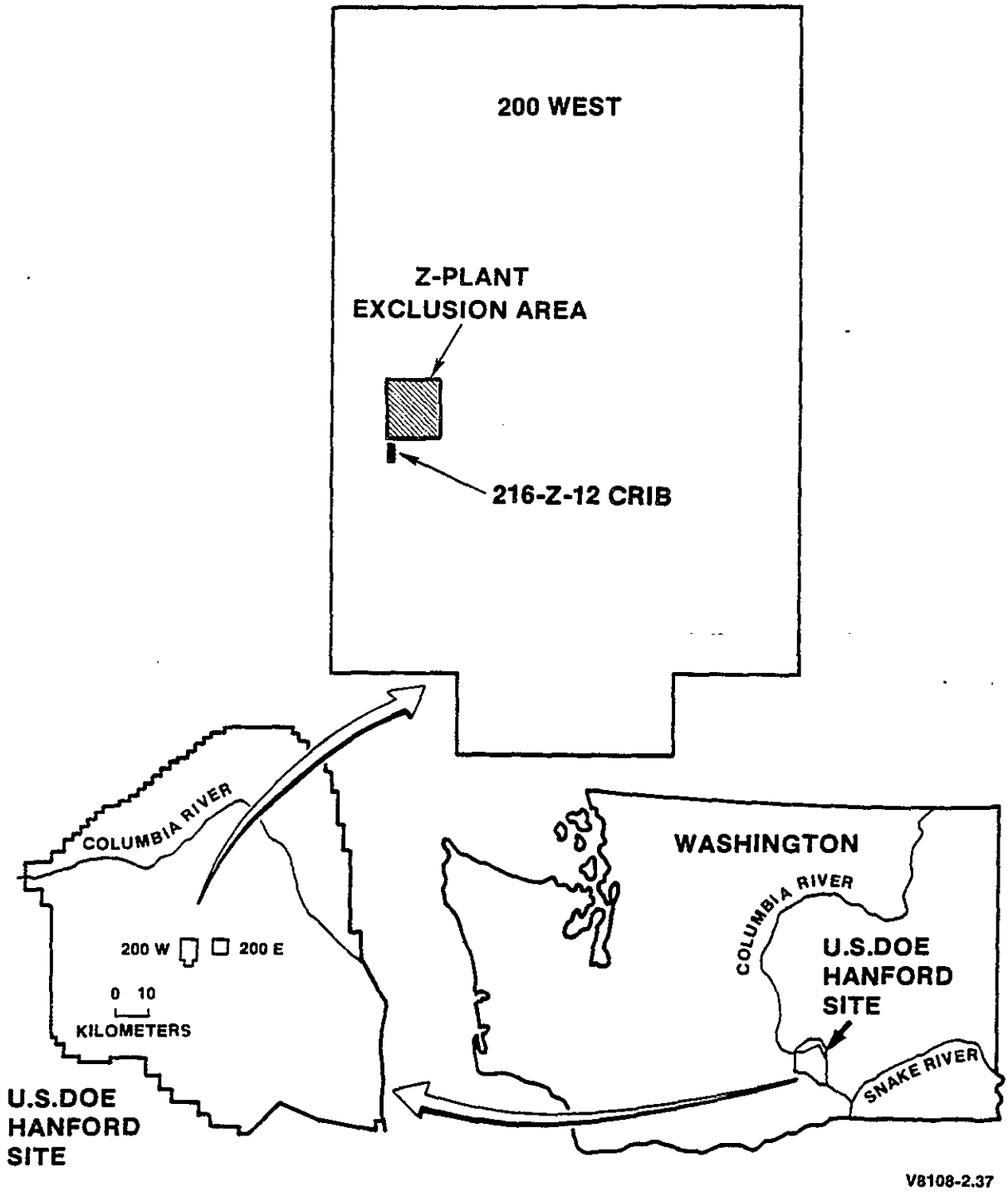


FIGURE 1. Location of the Hanford Site.

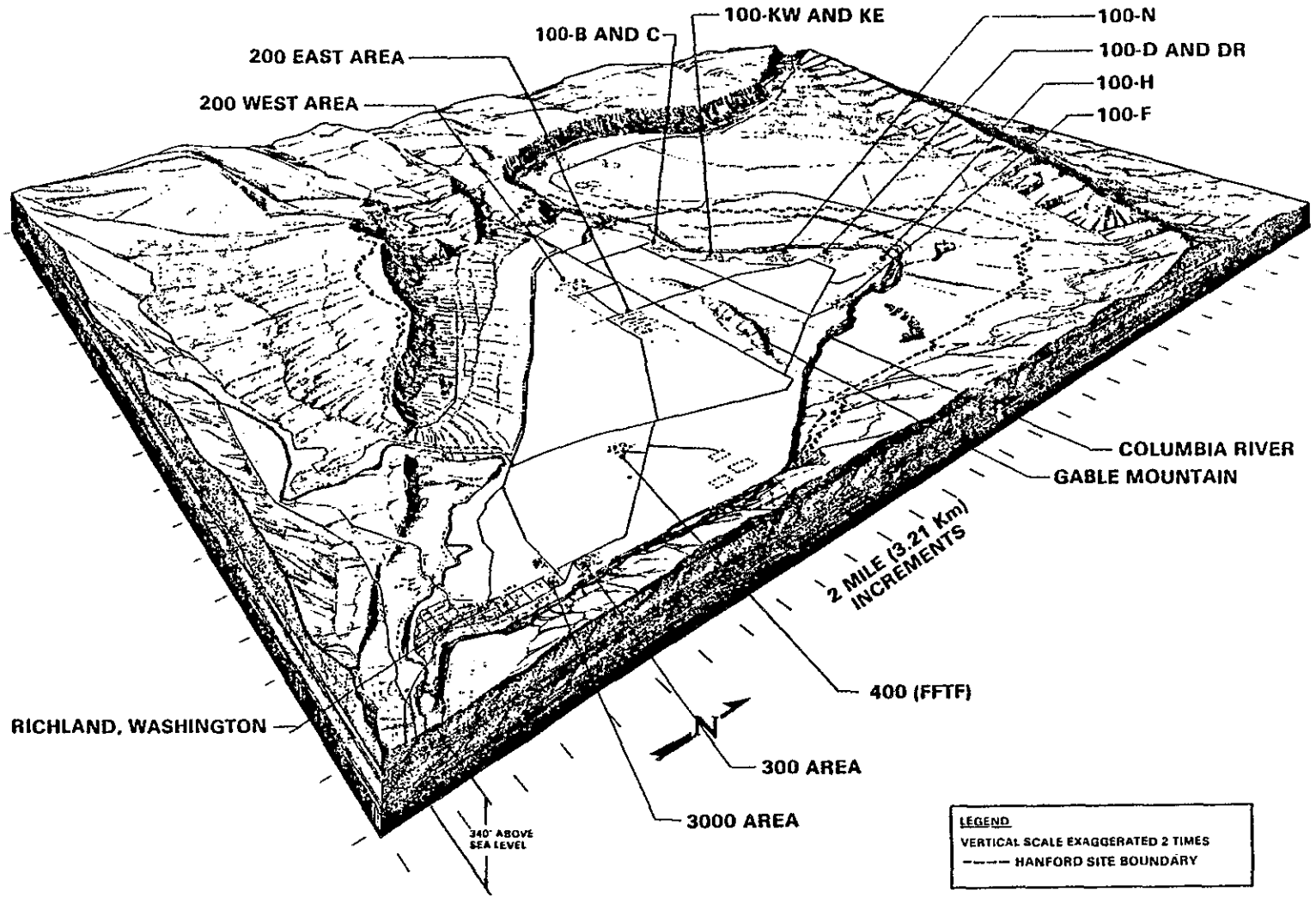

200 EAST AREA
200 WEST AREA
100-B AND C
100-KW AND KE
100-N
100-D AND DR
100-H
100-F
COLUMBIA RIVER
GABLE MOUNTAIN
2 MILE (3.21 Km) INCREMENTS
400 (FFTF)
300 AREA
3000 AREA
RICHLAND, WASHINGTON
340' ABOVE SEA LEVEL
N
LEGEND
VERTICAL SCALE EXAGGERATED 2 TIMES
HANFORD SITE BOUNDARY

TABLE 1. Cribs With Plutonium Inventories Greater Than 5 kg.[a]

Liquid waste disposal site	Plutonium inventory (kg)	Waste type
216-Z-1A[b]	58	High-salt
216-Z-9	38	High-salt
216-Z-12	25	Low-salt
216-Z-18	22	High-salt
216-Z-1 and -2	7.0	Low-salt, high-salt, and uranium recovery
216-Z-3	5.7	Low-salt

[a]From Liverman, 1975.

[b]Structures at Hanford are given a facility identification code to indicate the type of structure, its general location, and the specific structure. The 216-Z- prefix indicates a liquid waste disposal site (_16) in the 200 Areas (2__) that received waste from Z Plant (_Z_). Other examples mentioned in this report include the 241-Z- prefix for tank structures associated with Z Plant and the _99 prefix for wells. For wells, the 'W18' indicates the well is in section 18 in 200 West Area.

The cribs listed in Table 1 can be separated, on the basis of the type of process waste discharged, into two categories: high-salt or low-salt aqueous waste. (Uranium waste is similar in composition to high-salt waste.) High-salt aqueous waste (also identified as "CAW" or "AAW" waste, and occasionally associated with "organic" waste) was primarily a concentrated (5M to 6M), acidic (pH ∿1.0), sodium nitrate solution. In addition to the aqueous phase, organic liquids consisting of carbon tetrachloride (CCl_4), tributylphosphate (TBP), and dibutylbutylphosphonate (DBBP) occurred in saturation amounts in the aqueous phase, and were also discharged separately in batches. Less than 5% of the volume of high-salt aqueous waste discharged consisted of the organic component. Low-salt aqueous waste (also called D-6 waste) was primarily a dilute (∿0.15M), slightly basic (pH ∿8), sodium, fluoride, and nitrate solution. The chemical behavior of plutonium in these two waste types would be expected to differ.

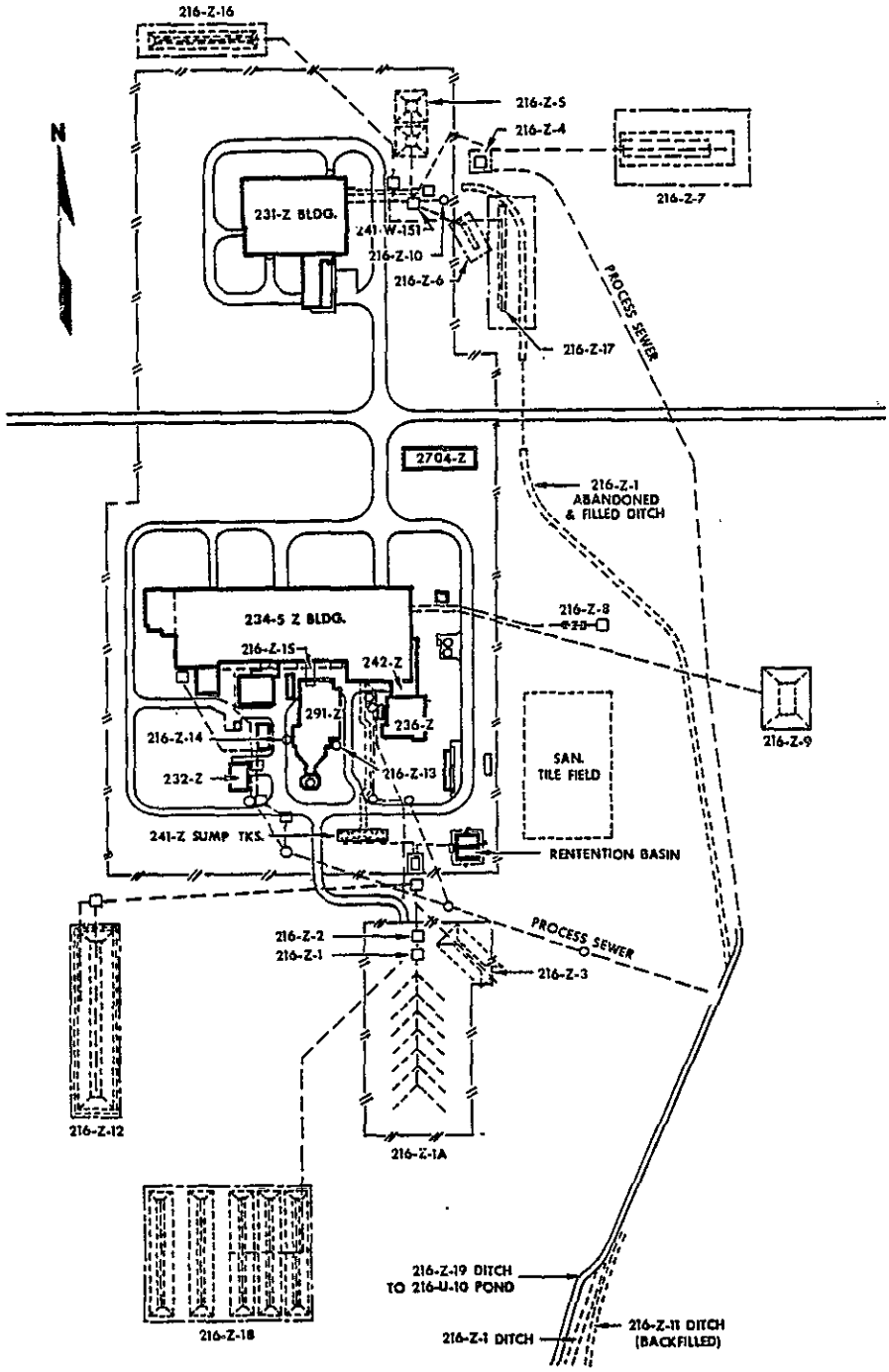


FIGURE 3. Z Plant Complex and Associated Liquid Waste Disposal Sites.

The 216-Z-1A Crib, which received high-salt aqueous waste, has been characterized by a previous field study (Price et al., 1979; Kasper et al., 1979a, 1979b). The 216-Z-9 Crib, which also received high-salt waste, has been partially characterized (Price and Ames, 1976; Smith, 1973) and was the subject of a project to recover plutonium from the zone of highest activity (Ludowise, 1978). The 216-Z-12 Crib is the largest crib that received low-salt aqueous waste and was selected for this study. The characterization of the distribution of plutonium and americium beneath the 216-Z-12 Crib will provide the required input to engineering studies. It will serve as a model for other cribs that received the same or similar waste type, and allow comparison of plutonium and americium transport by the two chemically different waste types as observed in the 216-Z-1A and 216-Z-12 Cribs.

216-Z-12 CRIB BACKGROUND

CONSTRUCTION DETAILS

The 216-Z-12 Crib is located immediately south of the Z Plant exclusion area (Figures 3 and 4). Design work on the 216-Z-12 Crib began in 1958 to provide a replacement for the 216-Z-3 Crib. The 216-Z-12 Crib design was typical for an aqueous waste crib (Liverman, 1975) (Figure 5). Figure 6 is a schematic of the 216-Z-12 Crib showing the major elements of the waste distribution system. Figures 7 and 8 show construction details of the crib obtained from engineering drawings and specifications.*

Construction began with a rectangular excavation having a 25- by 110-m (81- by 361-ft) surface dimension. Engineering drawings of the crib are inconsistent about the depth of the excavation; both 5.8 m (19 ft) and 6.1 m (20 ft) are reported. Measurements taken in the gauge wells during this study indicated a depth of 6.1 m (20 ft) to the bottom of the crib. The excavation had inward sloping sides, resulting in a 6.1- by 91.4-m (20- by 300-ft) floor dimension. Three gauge wells to measure liquid levels in the crib were emplaced on concrete pads on the crib bottom (Figure 9).

Clean, washed, and graded gravel was laid on the bottom of the crib. The gravel graded from 0.05- to 0.10-in.-diam particles on the bottom to 0.5- to 0.75-in.-diam on the top. The engineering drawings are inconsistent as to the thickness of this gravel fill; both 0.6 m (2 ft) and 1.2 m (4 ft) are reported. Measurements taken down the vent during this study indicated a thickness for the gravel fill of 0.9 m (3 ft). A single central distribution pipe was laid directly on top of the gravel layer with no slope. The distribution pipe consisted of 30-cm (12-in.) diam, 0.9-m (3-ft-) long segments of vitreous clay tile (VCT) pipe. Individual segments had six 0.6-cm (0.2-in.) perforations on the circumference at 7.6-cm (3-in.) intervals along the pipe

*Engineering drawings and specifications reported dimensions in English units. The exact English unit and metric equivalent (where appropriate) are reported.

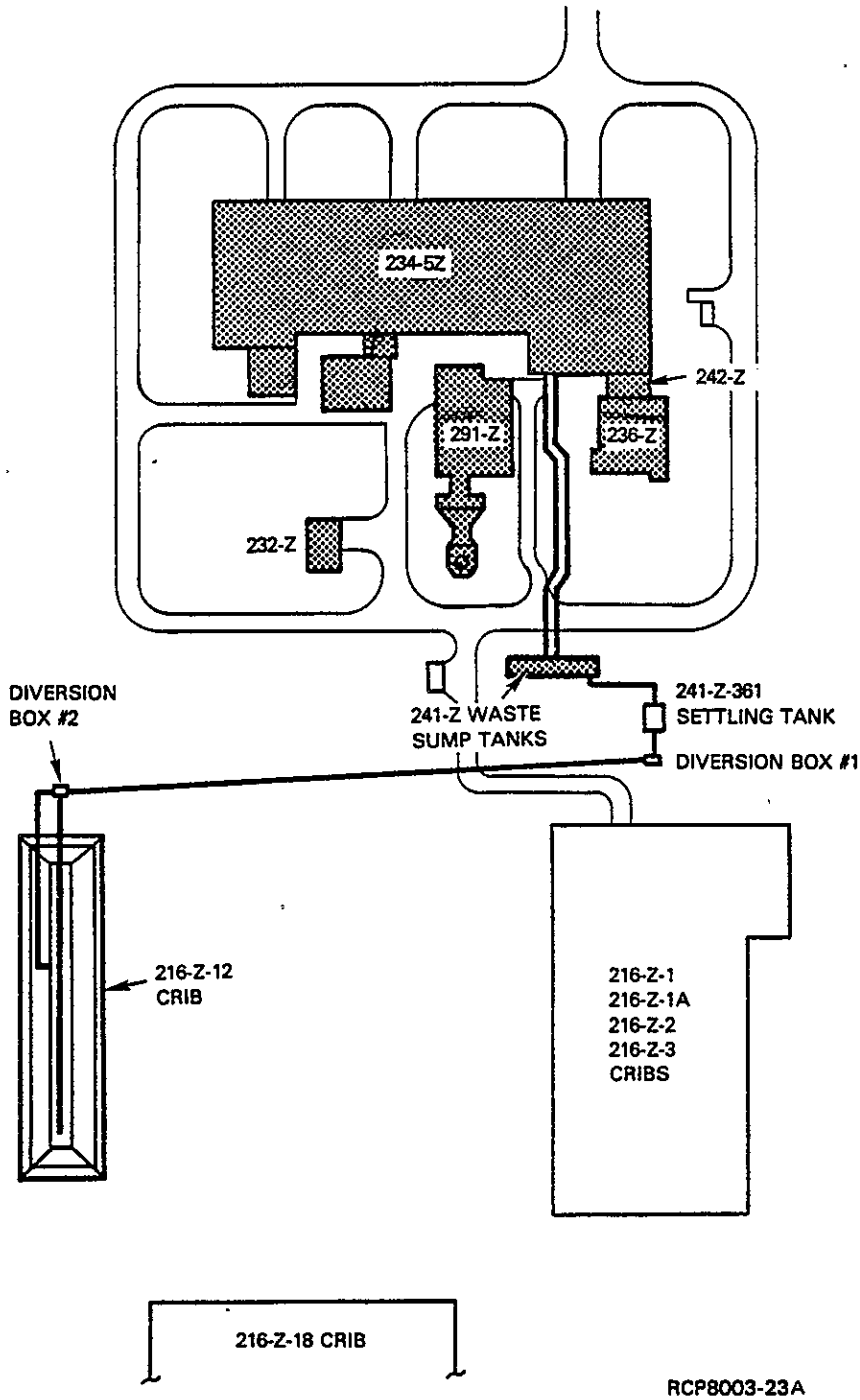


FIGURE 4. The 216-Z-12 Crib and Waste Piping System.

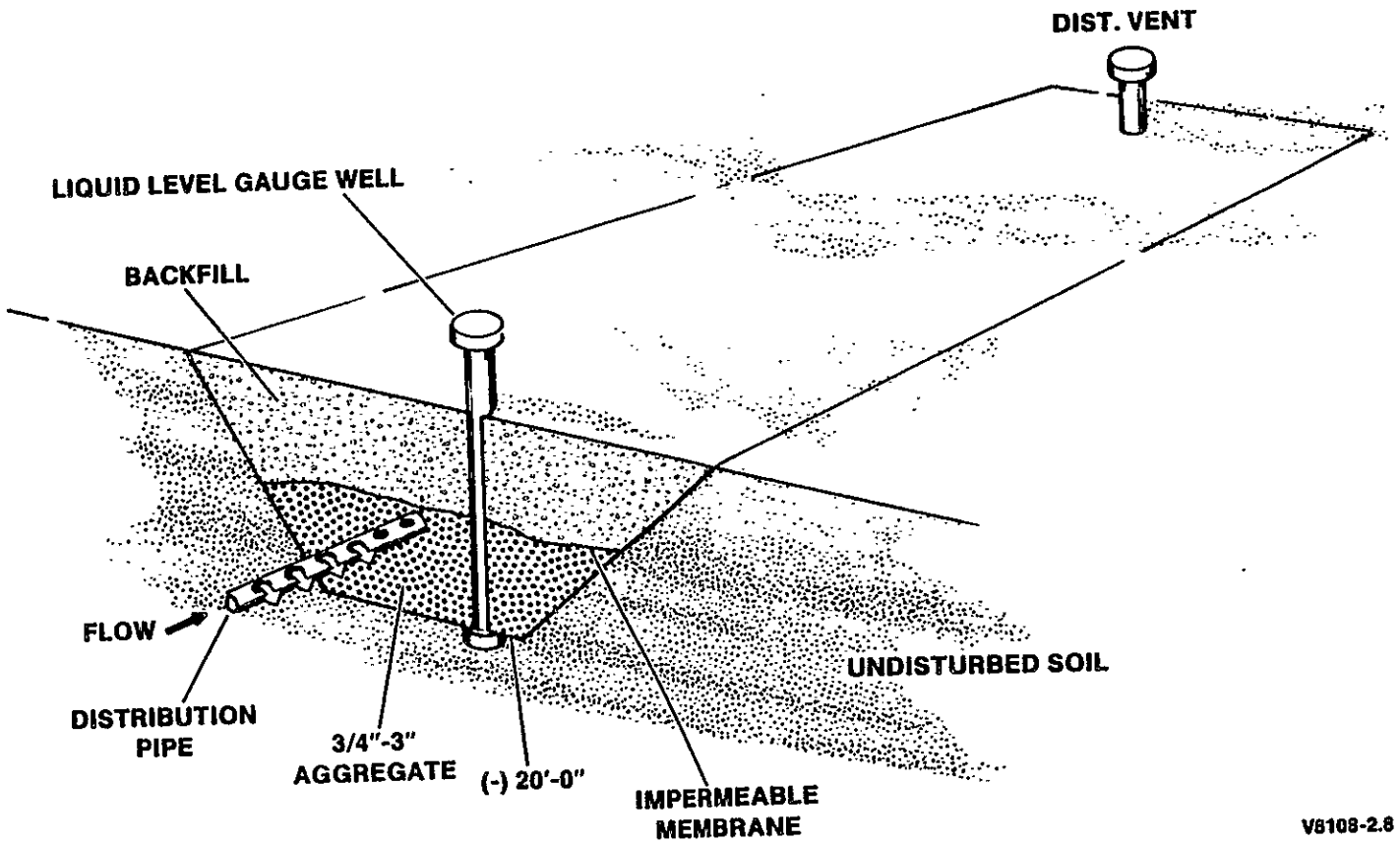


FIGURE 5. Typical Crib for Aqueous Waste.

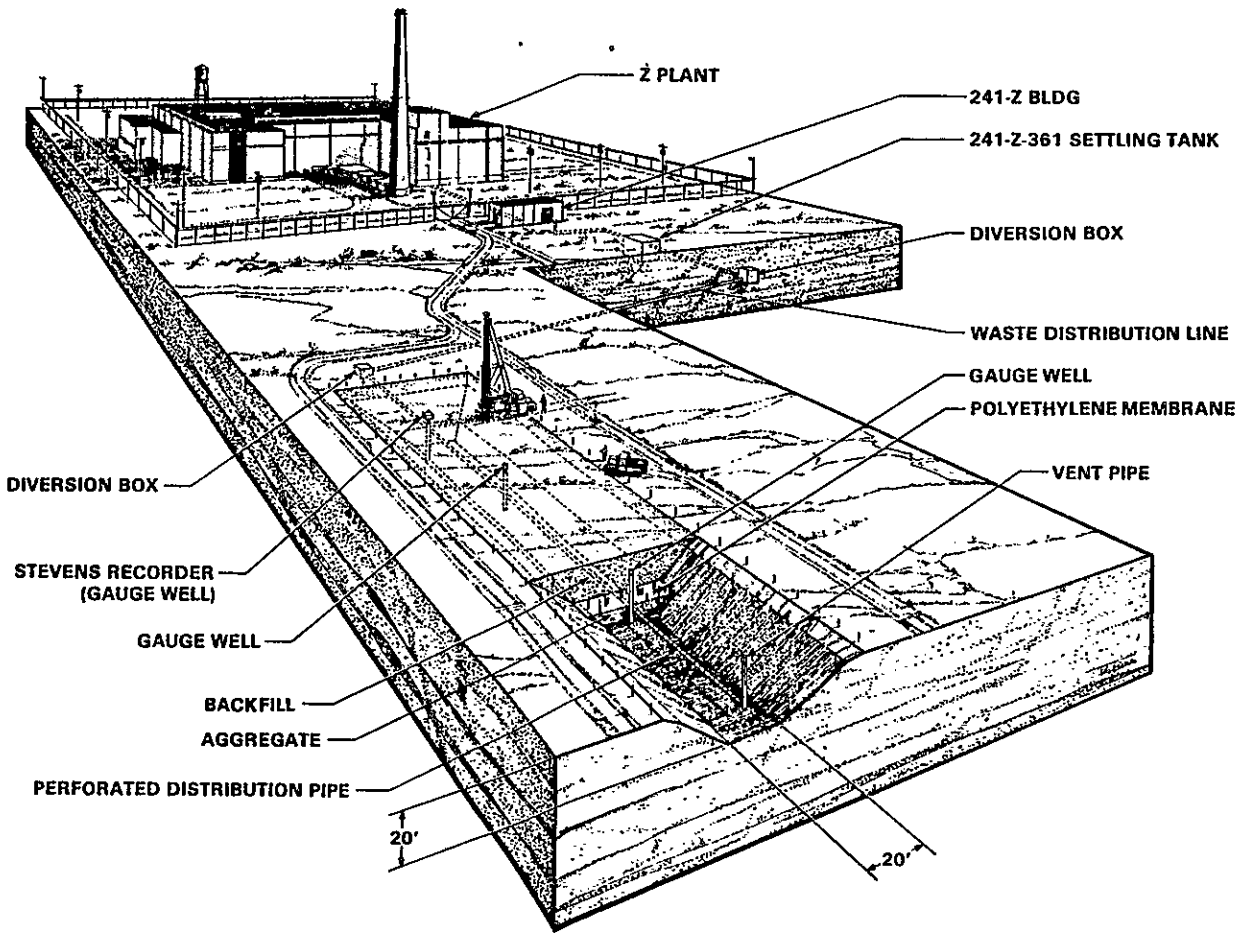


FIGURE 6. The 216-Z-12 Crib.

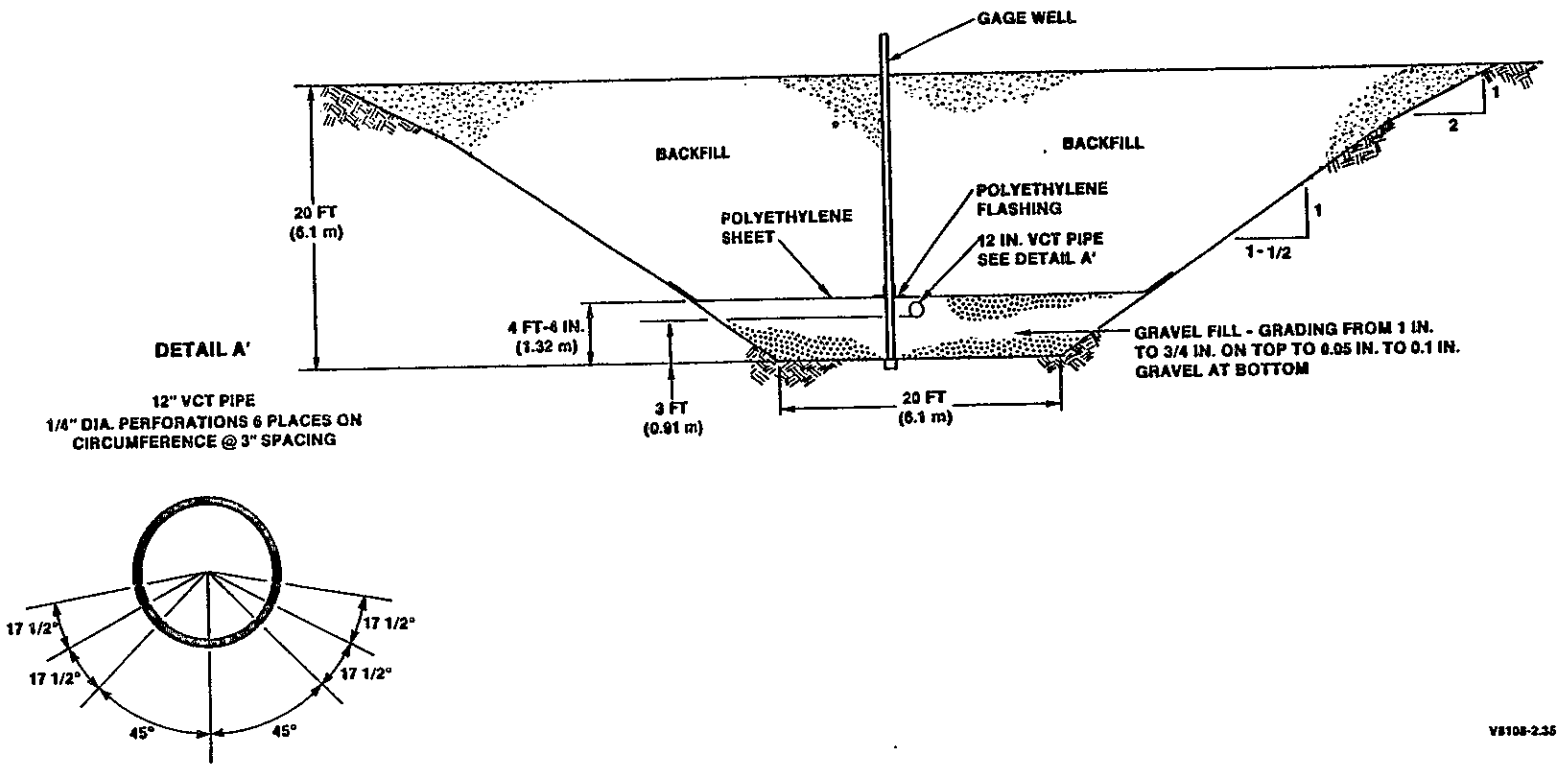


FIGURE 7. 216-Z-12 Crib Construction Details Perpendicular to the Distribution Pipe.

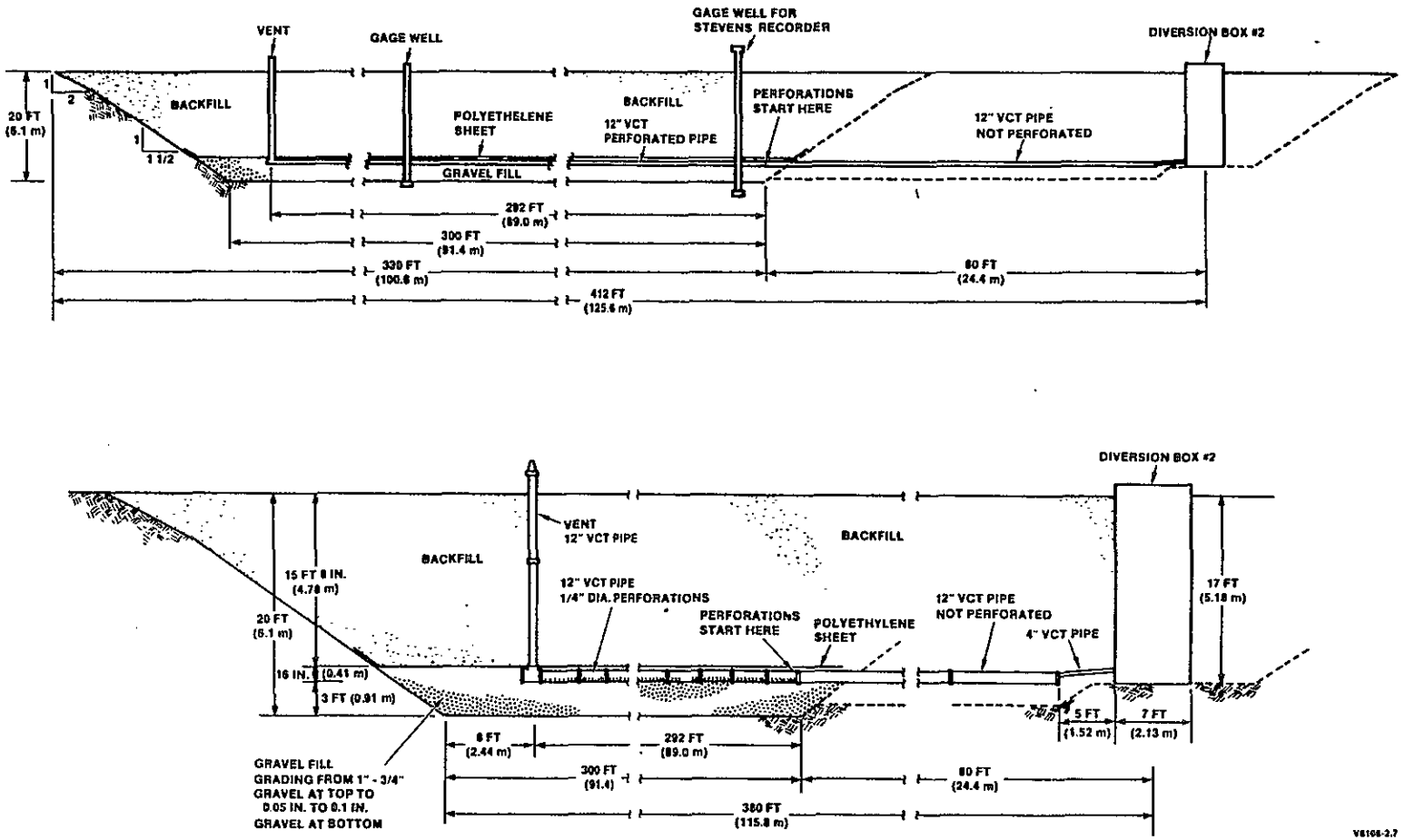


FIGURE 8. 216-Z-12 Crib Construction Details Along the Distribution Pipe.

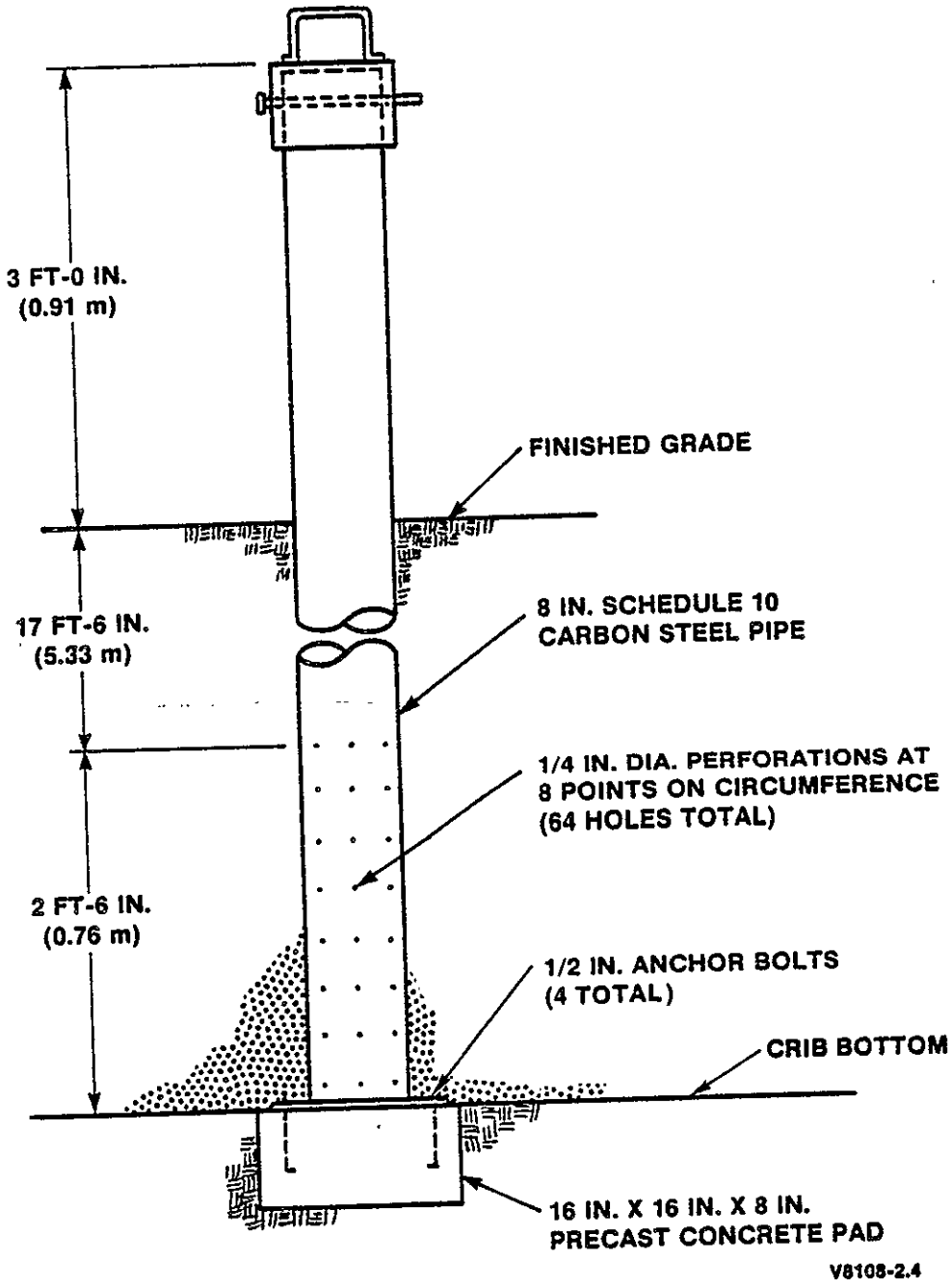


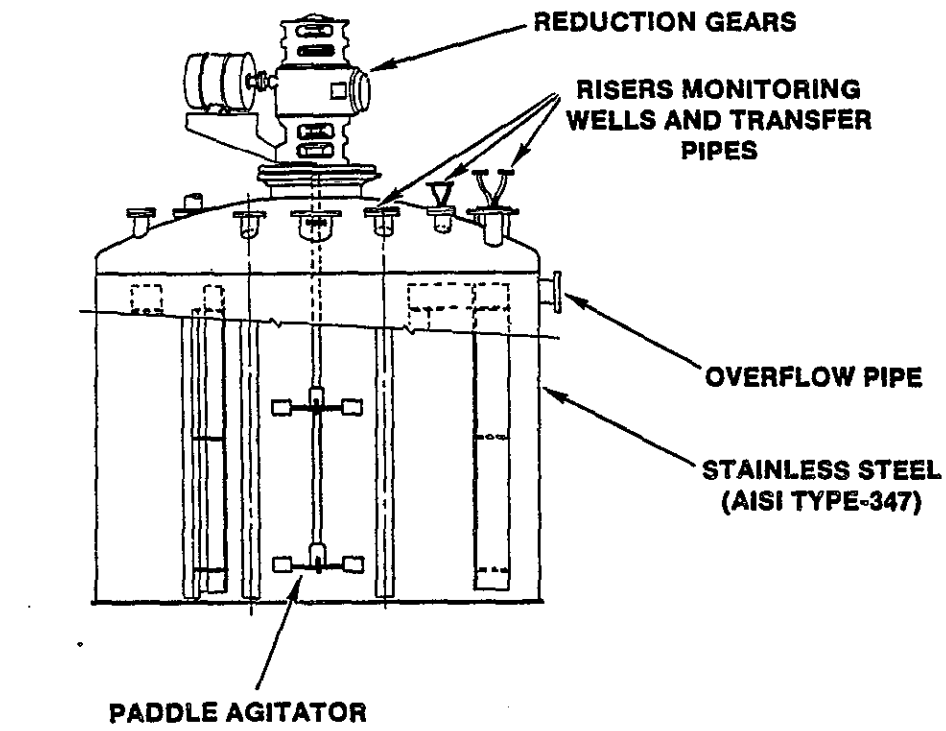
FIGURE 9. Typical Gauge Well.

(see Figure 7). Construction specifications indicated that the joints of the individual segments of pipe were to be sealed with oakum to prevent leaking. Sixteen inches of 0.75-in.- to 1.0-in.-diam gravel was laid around and over the pipe. A 0.020-in. (20-gauge) polyethylene sheet was laid on top of the gravel, extending at least 0.3 m (1 ft) up the sides of the excavation. The excavation was backfilled to grade.

As part of the 216-Z-12 Crib construction, a new diversion box (No. 2) and pipeline were laid to connect the crib to the existing waste distribution system at Diversion Box 1 (see Figure 4). The line from Diversion Box 2 to the VCT distribution pipe in the crib consisted primarily of 30-cm (12-in.) nonperforated VCT pipe in 3.0-m- (10-ft-) long sections. Engineering drawings indicated the sections were butted together and not sealed. (The engineering specifications only stipulated that the joints of the perforated VCT pipe be sealed.) Drawings indicated that the pipe was laid at the same level as the distribution pipe with no slope. A 10-cm- (4-in.-) diam VCT pipe connected the distributor box to the end of the 30-cm VCT pipe. Information on the size of the excavation required for emplacement of the diversion box and the nonperforated pipe was unavailable. The dimensions shown in Figure 8 were surmised from the engineering requirements.

WASTE OPERATIONS

Operations at Z Plant produced waste streams to the 216-Z-12 Crib. Individual waste streams were derived from drain systems in the development laboratory, the analytical laboratory, and from continuous process operations. Individual lines, numbered from D-4 to D-6, respectively, drained into tanks in the 241-Z Waste Storage Building (see Figures 3, 4, and 6). The building contains five stainless steel tanks, approximately 2.4 m (8 ft) high and 3.0 m (10 ft) in diameter, with an effective capacity of approximately 3,000 gal (12,000 L) (Figure 10). The individual tanks are numbered D-4 through D-8; the drain lines go to the tank with the same respective identification. Tanks D-7 and D-8 provided a reserve capacity for the D-6 Tank due to the large volume of liquid it received. A volume indicator in the D-6 Tank activated a pump when the



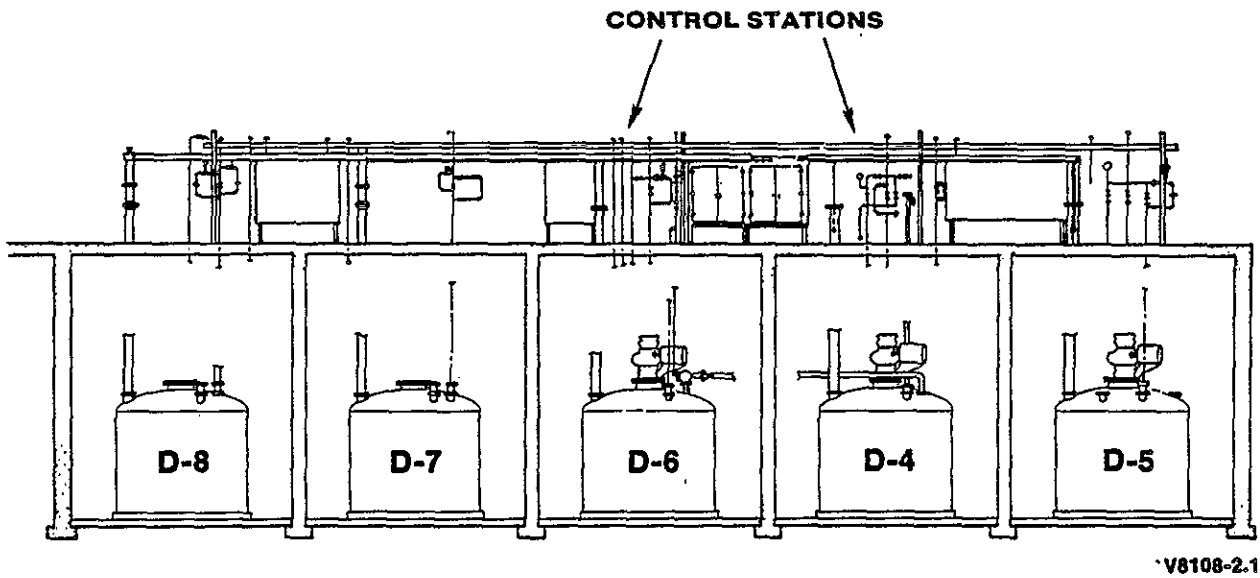


FIGURE 10. The 241-Z Building.

waste reached a preset level. The waste was transferred to the D-7 or D-8 Tank. A paddle agitator in the D-7 or D-8 Tank would stir the solution, and a sample of solution was taken from the tank for total alpha analysis. The waste was neutralized and jetted to the 241-Z-361 Settling Tank. The overflow then went to the crib.

Originally, the waste solution was neutralized to a pH of 10 by the addition of soda ash [$(Na,K)_2CO_3$] while the tank was stirred by the paddle agitator. After a year or two of operation, liquid sodium hydroxide (50%) was substituted for the soda ash. Starting in the mid-1960's, the solution was neutralized to a pH of 8. The change was based on previous experiments, which indicated greater sorption of plutonium on sediments from a solution with a pH of 8 (Rhodes, 1957). Occasionally, the wastes were only partially neutralized and were discharged slightly acidic.

The input to the D-6 Tank from continuous process operations required that the tank be discharged two or more times a day during normal operations. The D-4 and D-5 Tanks, because of smaller input volume, did not require a reserve capacity. These tanks were emptied when a preset volume was reached. A sample was taken for analysis, the solution was neutralized, and then discharged to the 241-Z-361 Settling Tank. Prior to April 1964, drain lines D-4 and D-5 were diverted to the D-6 Tank. In March 1972, the D-6 Tank failed and all drain lines were rerouted to the D-4 Tank.

The 241-Z-361 Settling Tank is an underground, steel-lined, reinforced concrete structure. Details of the tank construction are shown in Figure 11. The tank has a sloping bottom; inside, the tank is approximately 4 m (13 ft) wide, 8 m (26 ft) long and 5.5 m (18 ft) deep. Baffles over the inlet and overflow pipes reduced turbulent flow in the tank, which permitted particulates in the waste stream to settle out. Overflow from the tank flowed to the cribs by gravity feed.

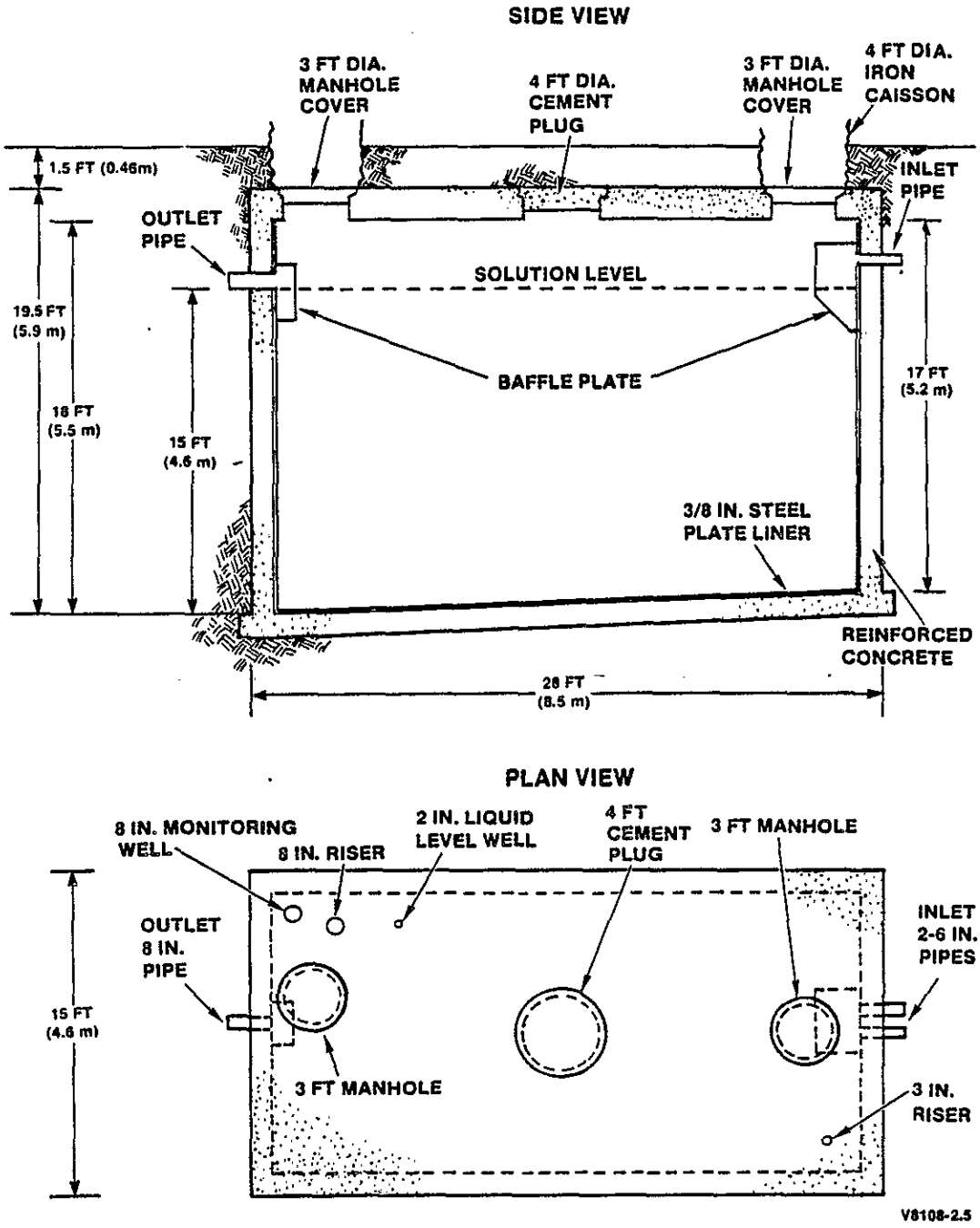


FIGURE 11. Details of the 241-Z-361 Settling Tank.

Waste Volume and Chemical Composition

Waste directed to the 216-Z-12 Crib was classified as low-salt, aqueous waste. Since experiments indicated that plutonium was quickly sorbed onto the sediments from the waste solution (Reisenauer, 1959), the 216-Z-12 Crib was not classified as a specific retention facility and the volume of waste that could be discharged was not limited.

An estimate of the total volume of liquid (and the plutonium content) discharged to the crib monthly is reported in Appendix A. This information comes from records of the 241-Z Building operations. Due to changes in Z Plant operations during the 14 years that the 216-Z-12 Crib was operational and the variability of day-to-day input, more detailed characterization of the waste streams may not be possible (Table 2). Existing references provide some information on the nature of the waste and permit a general picture of crib operations in the late 1960's. The following synthesis was based on documents and information provided by staff members familiar with Z Plant operations.

TABLE 2. Z Plant Processes That Discharged to the 216-Z-12 Crib.*

Process	Discharge period
Process operations (234-5Z)	6/49 to Present
Recuplex	7/55 to 4/62
Incinerator (232-Z)	12/61 to 5/73
Plutonium reclamation (236-Z)	5/64 to Present
Waste treatment (242-Z)	8/64 to 8/76

*Building noted in parentheses; see Figure 3 for location.

Sources of waste to the D-4, D-5, and D-6 drain lines are reported in Table 3. Also reported is an estimate of the volume of waste derived monthly from each source, an estimated inventory of plutonium discharged yearly from each source, and a general description of the composition of the waste from each source. A more detailed breakdown of the different sources is given in Appendix B.

The estimated average yearly contaminant contribution to the low-salt aqueous waste stream, circa 1969, is reported in Table 4. Using the information provided in Table 4 and the volume of waste discharged in 1969 (6,430,000 L) reported in Appendix A, the nominal composition of low-salt aqueous waste collected in the 241-Z Building can be estimated. The results are reported in Table 5. Low-salt waste, as collected in the tanks, was primarily a dilute sodium, fluoride, and nitrate solution with minor concentrations of calcium, magnesium, and aluminum. This solution was normally slightly acidic due to the presence of fluoride as hydrogen fluoride (HF). Neutralization of the solution to a pH of 8 using liquid NaOH would result in the waste discharge to the crib being primarily a dilute sodium fluoride and sodium nitrate solution.

The largest volume of liquid was derived from continuous process operations and was collected in the D-6 Tank. The bulk of the volume was derived from operation of fluorinator off-gas jets on the "button lines" where plutonium metal ingots (buttons) were produced. The off-gas jets are water aspirators used to provide a partial vacuum for the fluorinator. A fluorinator used hydrogen fluoride (HF) gas, reacting with plutonium oxide to produce plutonium fluoride (PuF_4). An off-gas jet provided the vacuum by which the HF was continually moved through the reaction vessel. When an off-gas jet was in operation, it used 20 to 30 L/min of water (approximately 600,000 L on the average per month); the resulting solution was approximately 0.06M HF (Knight et al., 1970).

The largest source of plutonium in the waste was derived from operation of the 232-Z Incinerator, although the volume of liquid was small. The incinerator burned a variety of materials, including organic liquids and plastic materials. The combustion gases passed through a

TABLE 3. Estimated Discharges of Low-Salt Wastes to the 216-Z-12 Crib, Circa 1969.[a]

Source	Volume (L/mo)	Plutonium (g/yr)	Remarks
D-4 Development Laboratory (plutonium chemistry laboratory and special processing hoods)	15,000	100	Miscellaneous lab chemicals from sink drains.
D-5 Analytical Laboratory area	40,000		Miscellaneous lab chemicals from sink drains.
D-6 Process Operations:			
232-Z Incinerator	2,000	600	Considerable sodium hydroxide from spent scrubber solution.
234-5Z Process operations	601,000	100	Primarily hydrogen fluoride from water for aspirators on button line.
236-Z Plutonium reclamation facility	17,000	10	Condensate from process concentrators, slight chemical contamination.
242-Z Waste treatment	27,000	60	Principally aluminum, calcium, and magnesium from batch ion exchange processes.

[a]From Knight et al., 1970.

number of filtering systems including a scrubber. In the scrubber, a sodium hydroxide solution was sprayed through the flow of gases onto a metal plate. The solution, which contained fine particulates, was sent to the D-6 Tank.

TABLE 4. Estimated Average Contaminant Contribution to the Combined Low-Salt Aqueous Waste Stream, Circa 1969.[a]

Contaminant	Weight/yr	Contaminant	Weight/yr
Plutonium	870 g	Aluminum	96 kg
Calcium	320 kg	Sodium	7,384 kg
Magnesium	128 kg	Fluorine	6,100 kg
Manganese	13 kg	Nitrate	19,904 kg

[a]From Knight et al., 1970.

TABLE 5. Nominal Composition of Low-Salt Aqueous Waste Collected in the 241-Z Building, Circa 1969.

Component	Concentration (M)
Sodium	0.05
Calcium	0.001
Magnesium	0.0008
Aluminum	0.0006
Manganese	0.00004
Fluoride	0.05
Nitrate	0.05

The Recuplex process, the Plutonium Reclamation Facility (PRF) in the 236-Z Building, and waste treatment operations in the 242-Z Building provided other contributions to the D-6 drain line at various times (see Table 2). The Recuplex and PRF wastes were primarily the condensate from process concentrators and normally contained minimal chemical and transuranic contamination. Input from waste treatment operations

contributed aluminium, calcium, and magnesium (Knight et al., 1970). The average composition of the low-salt waste suggested that this waste stream was also the source of most of the nitrate [probably nitric acid and sodium nitrate (see Table 4)].

The combined contribution from the Development and Analytical Laboratories to the D-4 and D-5 drain lines was small compared with the volume of waste and the amount of plutonium discharged to the D-6 drain line. Little information is available on the nature of the D-4 and D-5 drain line waste (see Table 3). It is assumed to be representative of the nature of experimental and analytical work done. Most development work probably was related to studies of separation processes in support of Z Plant operations and probably involved nitrate solutions and organic phases such as TBP-CCl_4 and DBBP-CCl_4. Very little information was obtained on the use of other organics with greater complexing ability. Laboratory personnel familiar with work performed in the 1960's referred to a study of organic agents to be used in decontamination work and to use of some exotic complexing agents for various studies, but individual documents have not been identified. Bulk organics were collected and disposed of in batches to the active high-salt crib, and thus, only a small volume of organics would have been discarded to the 216-Z-12 Crib. Because of this and the high concentration of other competing cations in the waste streams, even strong complexing agents are not expected to significantly affect the mobility of plutonium and americium.

Transuranic Inventory

Consistent with the purpose of the Hanford Site, plutonium is the predominant transuranic element discharged to the 216-Z-12 Crib. Most of the plutonium is expected to be weapons grade with an isotopic composition of approximately 93% ^{239}Pu, 6% ^{240}Pu, and 0.6% ^{241}Pu (Emery and Garland, 1974). In the late 1960's, fuel elements from power reactors were processed on a limited scale. The plutonium recovered from this fuel had a different isotopic composition, estimated as 55% ^{239}Pu, 25% ^{240}Pu, and 15% ^{241}Pu (Emery and Garland, 1974). The significant difference is in the increased amount of ^{241}Am that will eventually result from the decay of ^{241}Pu.

In the mid-1960's, development work was initiated to purify ^{238}Pu for use in energy sources. The ^{238}Pu was produced from the irradiation of ^{237}Np targets. Full-scale process operations eventually occurred offsite, but development work, including a large laboratory-scale pilot operation, was run in the Development Laboratory. Quantities of both ^{238}Pu and ^{237}Np might have been released to the drain lines, but in limited amounts.

Beta decay of ^{241}Pu produces ^{241}Am. In the crib, ^{241}Am activity gradually increases from the decay of ^{241}Pu discharged in the waste stream. Americium-241 was also separated from plutonium in the Recuplex process, the PRF, and the waste treatment process. Although americium was recovered and purified for other uses, waste streams containing americium were discharged to the high-salt waste cribs (216-Z-1A and 216-Z-18). Discharge of a separate americium waste stream to the 216-Z-12 Crib was not confirmed and the results of this study indicate it was unlikely. However, because of the possibility of several independent sources of americium and the variability of the ^{241}Pu content of the plutonium discharged to the 216-Z-12 Crib, it might not be possible to use americium activity to infer the plutonium content.

Small quantities of curium were purified in some laboratory work in the late 1960's to early 1970's. Very small quantities of curium may have reached the 216-Z-12 Crib through the D-4 drain line.

ENVIRONMENTAL SETTING

Various environmental factors can affect the present distribution of transuranic elements beneath the 216-Z-12 Crib. These factors are discussed briefly in this section. The environment at the Hanford Site is described generally in the environmental statement for Hanford (Liverman, 1975). The referenced documents in this report may be consulted for additional information.

Climate

The climate of the Hanford Site is semiarid because the site is located east of the Cascade Mountain Range, which forms a moisture

barrier to the general west-to-east weather flow patterns. Annual precipitation averages less than 18 cm for the site. Temperatures are mild, with an annual average temperature of 12°C.

The Hanford Site is subject to occasional high winds. Prevailing winds at the 200 Areas are from the north-northwest through northwest, although the strongest winds are from the southwest. The highest peak wind gust measured was from the southwest at 116 km/h. Winds with peak gusts of 64 km/h or greater have been measured on the average at least once in every month.

Biology

Eight major kinds of shrub-steppe communities make up the vegetation mosaic of the Hanford Site. A sagebrush/cheatgrass community is the dominant vegetative type in the 200 Areas. During construction of the 216-Z-12 Crib, the area was extensively disturbed, destroying the native vegetation. The crib site is presently populated by Russian thistle (*Salsola kali*), cheatgrass (*Bromus tectorum*), and rabbit brush (*Chrysothamnus* species).

The dry climate of the Hanford Site favors some plant species with deep roots that could penetrate to the contaminated sediments. In the absence of complexing agents, however, plutonium and americium are not normally concentrated in plants (Francis, 1973; Price, 1973; Watters, 1978). Since primarily plutonium appears to have been discharged to the site and americium decayed in situ, uptake by plants is not anticipated. The polyethylene sheet and coarse gravel fill used in the bottom of the crib act as a biobarrier to limit penetration of plant roots. Sampling of plants taken at the 216-Z-12 Crib indicate no uptake has occurred.

Burrowing of animals into waste sites has the potential of bringing contaminated sediment to the surface (Liverman, 1975; O'Farrel and Gilbert, 1975). The proximity of Z Plant to the 216-Z-12 Crib minimizes the potential for large mammals at the site. The depth to the contaminated sediment and presence of the coarse gravel fill limit the potential for animal intrusion.

Hydrology

Movement of water at the 216-Z-12 Crib could transport radionuclides from their present location. The hydrology of the site is discussed in terms of surface, vadose zone, and ground-water hydrology.

Surface Hydrology. The dry climate and high moisture infiltration rates due to highly permeable surface soils over most of the Hanford Site reduce the importance of surface hydrology (surface runoff). Most of the 200 West Area landscape lacks evidence of water erosion and, except for localized areas of short steep slopes, surface runoff appears to be negligible.

Vadose Zone Hydrology. The rapid infiltration of precipitation and subsequent deeper percolation into the vadose zone create the potential for water to reach wastes beneath the 216-Z-12 Crib. Depth of water penetration is a function of precipitation duration and intensity. Long-term lysimeter experiments at Hanford have assessed precipitation penetration depths under near-natural conditions (Jones, 1978; Brown and Isaacson, 1977). Moisture was found to penetrate to depths greater than 5 m during the experiments (less than 10 years), but deeper percolation was negligible.

Highest soil moisture levels and deepest moisture penetrations may be expected in early spring, when low evapotranspirative demand has allowed moisture from winter snow and rain to accumulate in the soil. During years of extraordinarily high winter precipitation, some ground-water recharge through vadose zone transport may be possible. Normally, the deeply penetrating moisture moves back to the atmosphere in response to evapotranspirative demand. This upward movement of moisture has the potential for transporting water-soluble radionuclides toward the soil surface (Routson et al., 1981). Plutonium is not significantly water soluble under environmental conditions. The results of this study indicated that the bulk of the plutonium in the waste stream sorbed onto the sediments within a meter of the point of discharge with only very limited migration beyond a few meters. Dissolution and migration of the plutonium by movement of water in the vadose zone would not be expected to occur at the 216-Z-12 Crib.

Waste fluid movement through the vadose zone is affected by the heterogenous sediment beneath the crib. Horizontal layering of different sediment types impedes moisture transport across the boundary between sediment types. The result of reduced flow is lateral spreading of the liquid at the interface. Lateral spreading is desirable because of the greater volume of vadose zone sediment that comes in contact with the waste.

Ground-Water Hydrology. The water table beneath the 216-Z-12 Crib is 62 m below the ground surface, 144 m above mean sea level. The unconfined aquifer is naturally recharged in the Cold Creek and Dry Valley areas west of the 200 Areas. As discussed in "Vadose Zone Hydrology," recharge due to precipitation from the 200 West Area surface to the ground water is negligible. Artificial recharge areas such as cribs have a local effect but the overall flow pattern of the ground-water aquifer from west to east, to the Columbia and Yakima Rivers, prevails (Newcomb et al., 1972; Graham et al., 1981).

Geology

Radionuclide waste disposal to the ground has been possible because waste-sediment interactions can retain the radionuclides on the sediment column. Waste sediment interactions include chemical and physical processes. Chemical processes include the sorption of the radionuclides onto the sediment and chemical changes to the waste solution composition that result in greater sorption of the radionuclides. Physical processes include filtration of particulate material in the waste stream, and the retarding of waste liquid flow at sediment type interfaces, which results in lateral spreading as discussed in "Vadose Zone Hydrology." A knowledge of the geology beneath a liquid waste disposal site is thus required to interpret radionuclide distribution.

The general stratigraphy beneath the 216-Z-12 Crib is summarized briefly. The geology of the 200 Areas is discussed in detail in Tallman et al. (1979).

Figure 12 shows a simplified stratigraphic cross section of the sediments beneath the 200 West Area near the 216-Z-12 Crib. The 200 West Area is located on a broad bar of sand and gravel, locally called the 200 Areas Plateau, deposited by the spreading flood waters of catastrophic Pleistocene floods. The unconsolidated sands and gravels deposited during the floods are identified as the Hanford formation (informal name). At the 216-Z-12 Crib, the Hanford formation is 36 m thick.

A surficial eolian deposit at the 216-Z-12 Crib was derived from the wind reworking the underlying Hanford formation sediments. The deposit was removed during excavation of the crib and returned as part of the backfill. It is identified by the finer texture of the backfill compared with the underlying Hanford formation sediments. The unit also appears outside the crib excavation in wells 152 and 153.

The fine sand and silt below the Hanford formation is identified as early "Palouse" soil. It is so named because of its similarity to the extensive loess accumulations of the same name in eastern Washington. Palouse soil is thought to be the wind-reworked and -redeposited fine-grained sand and silt of the underlying Ringold Formation sediments. Beneath the 216-Z-12 Crib, the surface of the early Palouse Soil is at a depth of 39 m and the unit is 2 m thick.

Beneath the early Palouse soil is the Ringold Formation, which has four textural units; they are identified as the upper, middle, lower, and basal. The upper Ringold sediments are primarily medium to fine sands with silt and clay interlayers. The surface of the upper Ringold unit is identified by a well-developed caliche horizon. At the 216-Z-12 Crib, the surface of the upper Ringold is at 41 m depth and the unit is 12 m thick. The middle Ringold bed consists of well-rounded pebbles and small cobbles with coarse to fine sand and silt filling the interstitial spaces. The surface of the middle Ringold occurs at a depth of 53 m below the ground surface. The water table occurs in the middle Ringold at a depth of 62 m below ground surface, 144 m above mean sea level (Tallman et al., 1979). At the 216-Z-12 Crib, the middle Ringold's thickness is estimated as 85 m.

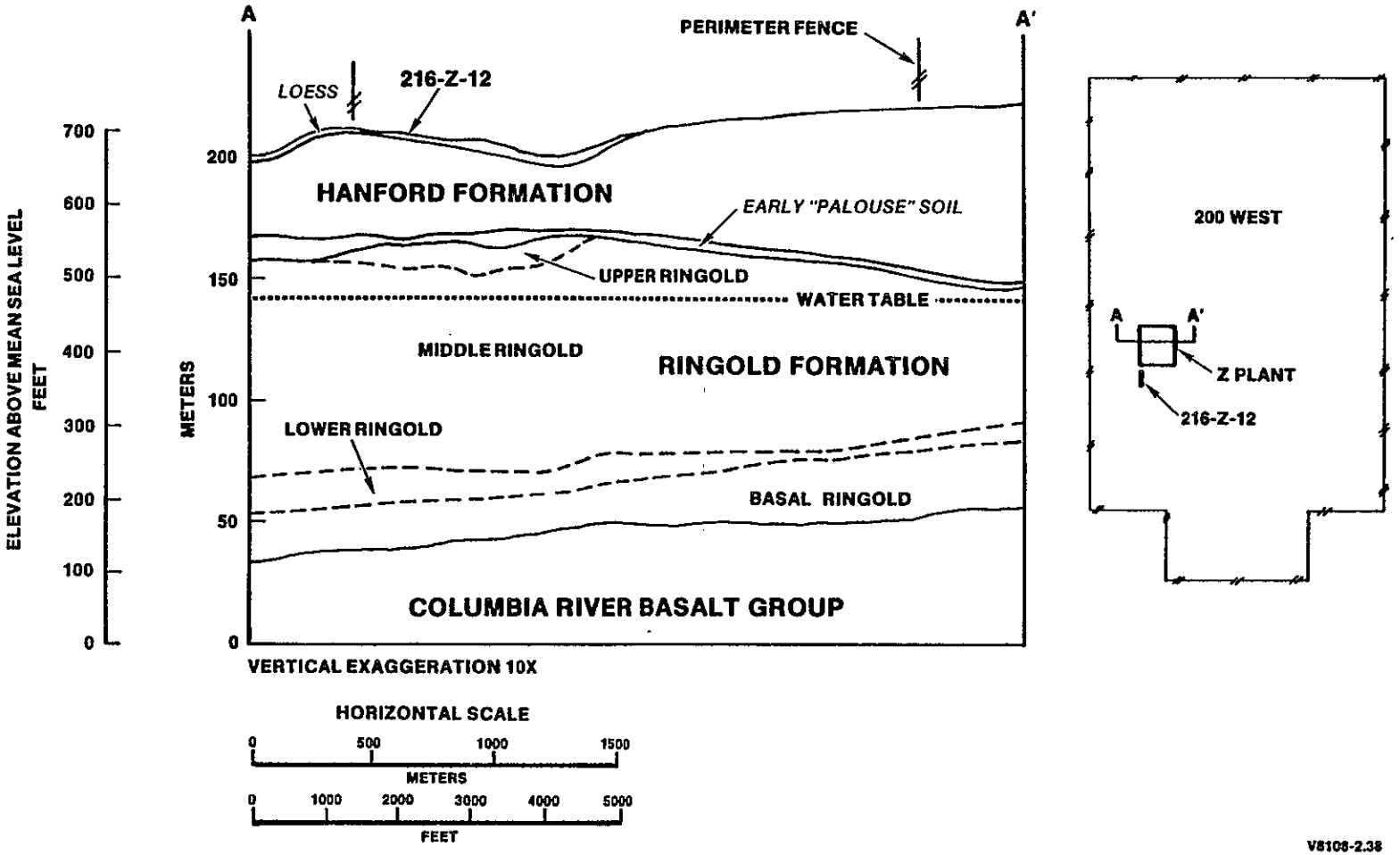


FIGURE 12. Stratigraphic Cross Section Beneath the 200 West Area.

The lower Ringold ranges from a silty coarse to medium sand to a sandy silt. Beneath the 216-Z-12 Crib, the thickness of the lower Ringold is estimated as 15 m. The basal Ringold bed consists of a silty, sandy gravel. Beneath the 216-Z-12 Site, the thickness of the unit is estimated as 20 m. The basal Ringold bed overlies the Elephant Mountain Member of the Saddle Mountains Basalt of the Columbia River Basalt Group. The entire basalt group beneath the Hanford Site consists of a 1,500-m-thick sequence of basalt flows and interbedded clastic and volcaniclastic sediments.

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PREVIOUS INVESTIGATIONS OF THE 216-Z-12 CRIB

Several investigations of various aspects of the 216-Z-12 Crib have been conducted before the current study. The results of these previous studies were used both to plan the current work and to supplement the results of the current study. These earlier studies are discussed in the following sections, "Previous Field Studies" and "Previous Laboratory Studies."

PREVIOUS FIELD STUDIES

Well Drilling Investigations

Before 1980, 18 wells were drilled in and around the 216-Z-12 Crib (Figure 13). The primary purpose of these wells was to provide information on the movement of the disposed waste. Two wells (2 and 5)* were drilled in 1958 during crib construction to monitor ground water beneath the crib. Two additional monitoring wells (8 and 69) were added in 1967 as part of an upgrading of the monitoring system around Z Plant.

In 1967, the 216-Z-1A and 216-Z-12 Cribs were studied to determine if discharged waste was being dispersed over the entire effective bottom area of the cribs (Crawley, 1967). As part of the study, six shallow wells (70 through 75) were drilled in the 216-Z-12 Crib (Figure 14). "The wells were drilled until alpha contamination was encountered, or a few feet below where it could be expected to be encountered" (Crawley, 1967). Using a portable radiation survey instrument ("poppy"), activity was detected in the three northernmost wells (70, 71, and 75) nearest the waste inlet end of the distribution pipe at the crib bottom level [approximately 6.1 m (20 ft)]. No activity was detected in the remaining three wells (72, 73, and 74) in the southern two-thirds of the crib. The location of these wells, next to the distributor pipe and through the bottom of the crib, indicated that no detectable waste was

*As discussed previously, all wells mentioned are prefixed by 299-W18-.

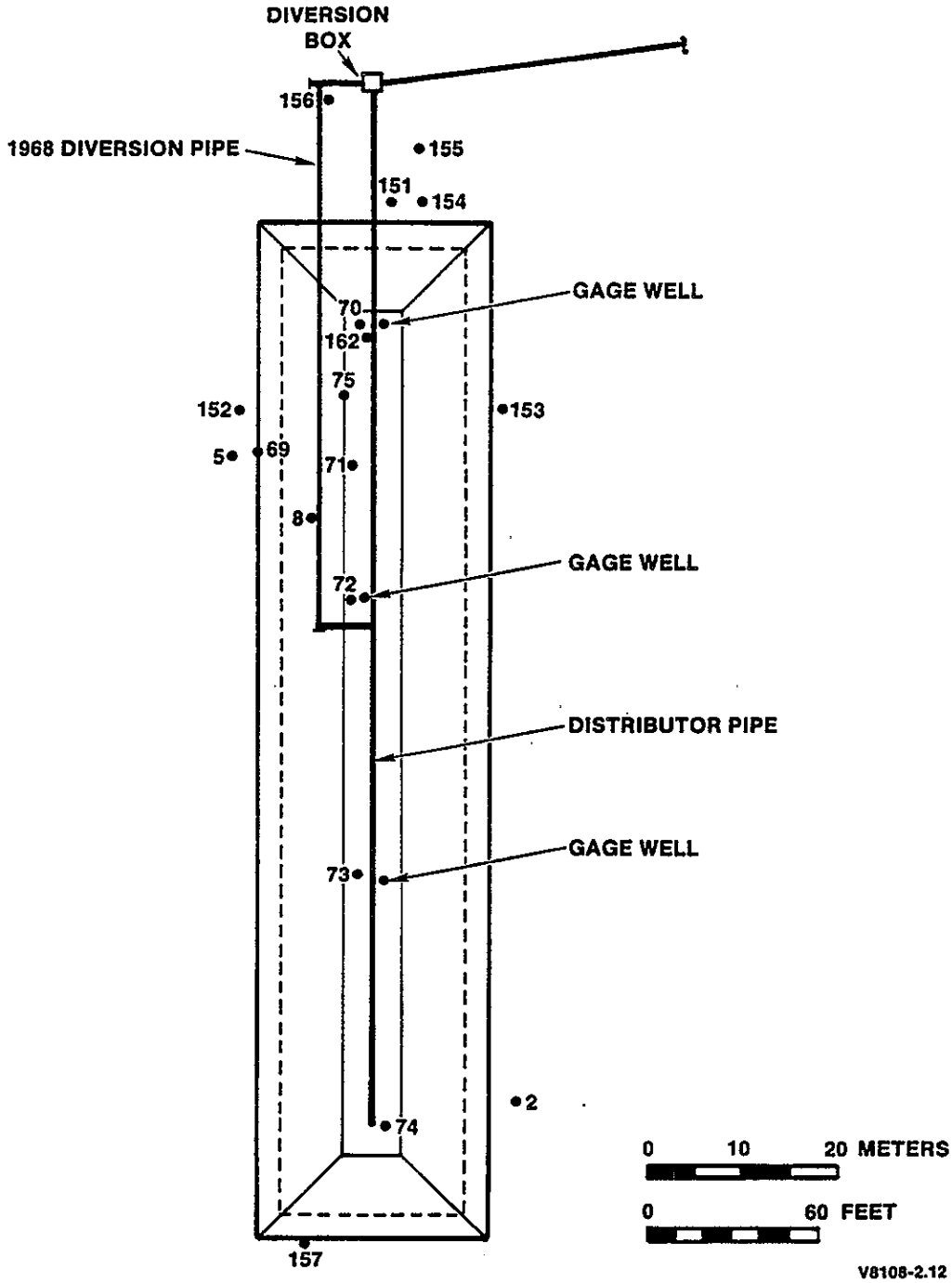
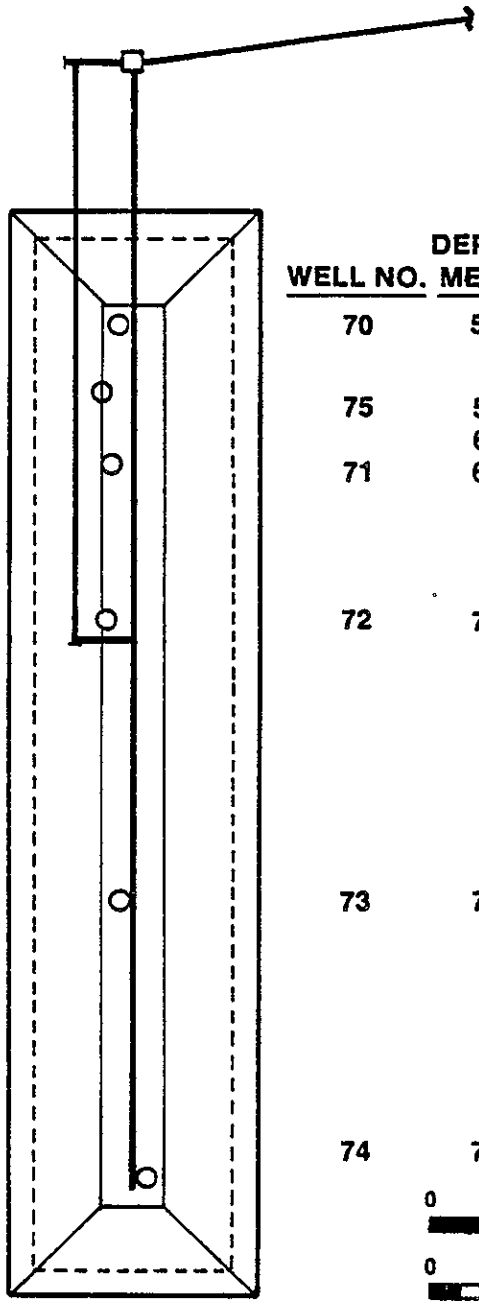


FIGURE 13. Existing Wells at the 216-Z-12 Crib Before January 1980.



WELL NO.	DEPTH DRILLED METERS (FEET)	CONTAMINATION ENCOUNTERED AND/OR REMARKS
70	5.79 (19)	220,000 DPM (BY JUNO IN FINE SAND)
75	5.79 (19)	5,000 DPM BY POPPY
	6.24 (20.5)	> 40,000 DPM BY POPPY
71	6.00 (19.67)	> 40,000 DPM BY POPPY
72	7.92 (26)	NONE
73	7.62 (26)	NONE
74	7.62 (26)	NONE

0 10 20 METERS

0 60 FEET

NOTE: DPM = DISINTEGRATIONS PER MINUTE

V8108-2.11

FIGURE 14. Results of the 1967 Drilling Study.

reaching this portion of the crib. These results confirmed calculations that suggested the rate of flow of waste to the crib was insufficient to distribute the liquid over the entire crib bottom. As a result, in July 1968, a diversion pipe was installed in the crib, bypassing the first 30 m (100 ft) of the distributor pipe (see Figure 13). The distributor pipe was plugged just north of where the diversion pipe joined the distributor pipe, and at the diversion box, to prevent flow to that section. From July 1968 to May 1973, when the crib was retired, waste was discharged only to the southern two-thirds of the crib.

Well 70, which had been drilled in 1967 to 5.8 m (19 ft), was deepened in 1968 to approximately 10.7 m (35 ft) (Crawley, 1969). Core samples were obtained at approximately 0.6-m (2-ft) intervals. Selected samples were analyzed for plutonium with a lithium-drifted germanium [Ge(Li)] detector system. Table 6 presents the results of the analyses Only the sample located 0.61 m (2 ft) below the crib bottom had measurable plutonium, with an activity of 3.1 nCi/g of soil (5×10^{-8}g Pu/g of soil). The results of this study suggest that the highest plutonium activity was located within 30 cm of the bottom of the crib.

In 1976, another study of the 216-Z cribs resulted in the drilling of eight new wells in and around the 216-Z-12 Crib and the deepening of one existing well (Figure 15). Four shallow wells (151, 154, 155, and 156) were drilled at the north end of the crib. Detectable alpha activity was encountered at approximately 5.2 m (17 ft) in all four wells. Well 156 was drilled through the zone of alpha activity to a final depth of 7.6 m (25 ft). The layer of alpha activity was found to be only several centimeters thick.

Well 75, which was originally drilled to 6.24 m (20.5 ft) in 1967, was deepened in 1976 to 12.8 m (42 ft). Because of the anticipated high levels of activity, elaborate precautions were undertaken to prevent the spread of contamination. A tripod rig was used for drilling and a specially designed glovebox used for handling the contaminated material was placed over the well (Figure 16). Samples were sealed out of the glovebox in double plastic bags for analysis and storage. Samples were analyzed for plutonium and americium using a Ge(Li) detector system.

The ^{239}Pu gamma-ray at 414 keV, the ^{240}Pu gamma-ray at 104 keV, and the ^{241}Am gamma-ray at 59.6 keV were counted. Five samples selected from the bottom of the well were also analyzed by alpha energy analysis (AEA). The results of the analyses are given in Table 7 and plotted in Figure 17. Sediment descriptions recorded in the drill log are also presented and graphically summarized by a lithologic log. The results of the analyses plotted in Figure 17 supported three observations.

TABLE 6. Plutonium Soil Penetration in Well 299-W18-70.[a]

Sample	Depth from bottom of crib [m (ft)]	Grams plutonium/ gram of soil	Field radiation survey measurement[b] (counts/min)
1	0.61 (2)	5×10^{-8}	2,000
2	2.44 (8)	Nondetectable	bg[c]
3	1.83 (6)	Not analyzed	bg[c]
4	3.05 (10)	Not analyzed	bg[c]
5	3.66 (12)	Not analyzed	bg[c]
6	3.81 (12.5)	Nondetectable	bg[c]
7	4.11 (13.5)	Not analyzed	bg[c]
8	4.42 (14.5)	Not analyzed	bg[c]
9	4.57 (15)	Not analyzed	bg[c]
10	4.88 (15)	Nondetectable	bg[c]

[a]Taken from Crawley, 1969.

[b]Field survey measurements taken using a Geiger (G-M) instrument. Readings are a qualitative indication of radioactivity reported as counts per minute.

[c]Background for the G-M instrument was 200 counts/min.

First, the highest level of activity was located within 1 m below the crib bottom. Since the well had originally been drilled to 6.24 m (20.5 ft), which is below the bottom of the crib, samples with a higher activity might not have been recovered.

Second, activity greater than 10 nCi/g (10,000 pCi/g) was found to occur to approximately 3 m (9.8 ft) below the bottom of the crib, 10 m

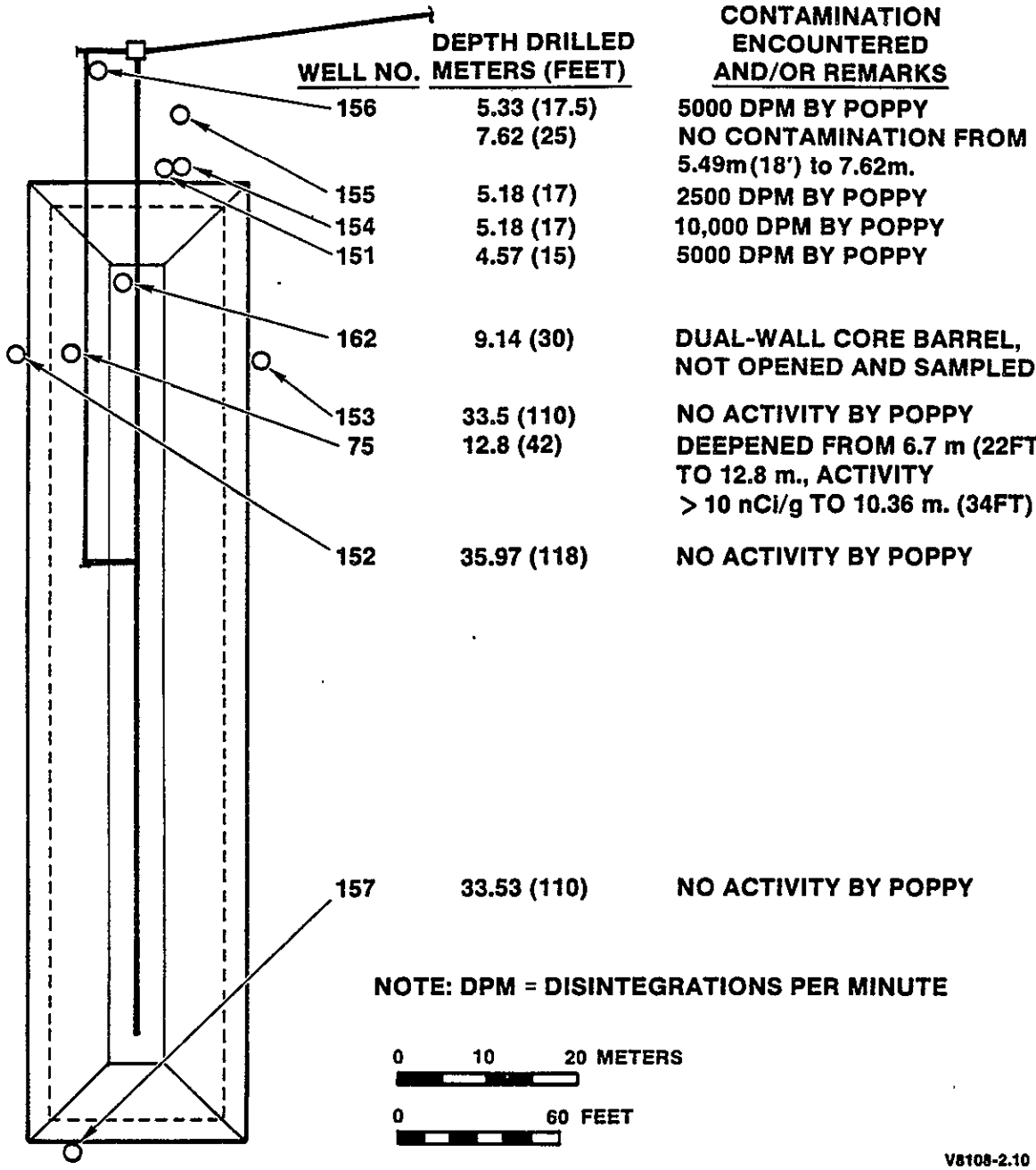


FIGURE 15. Results of the 1976 Drilling Study.

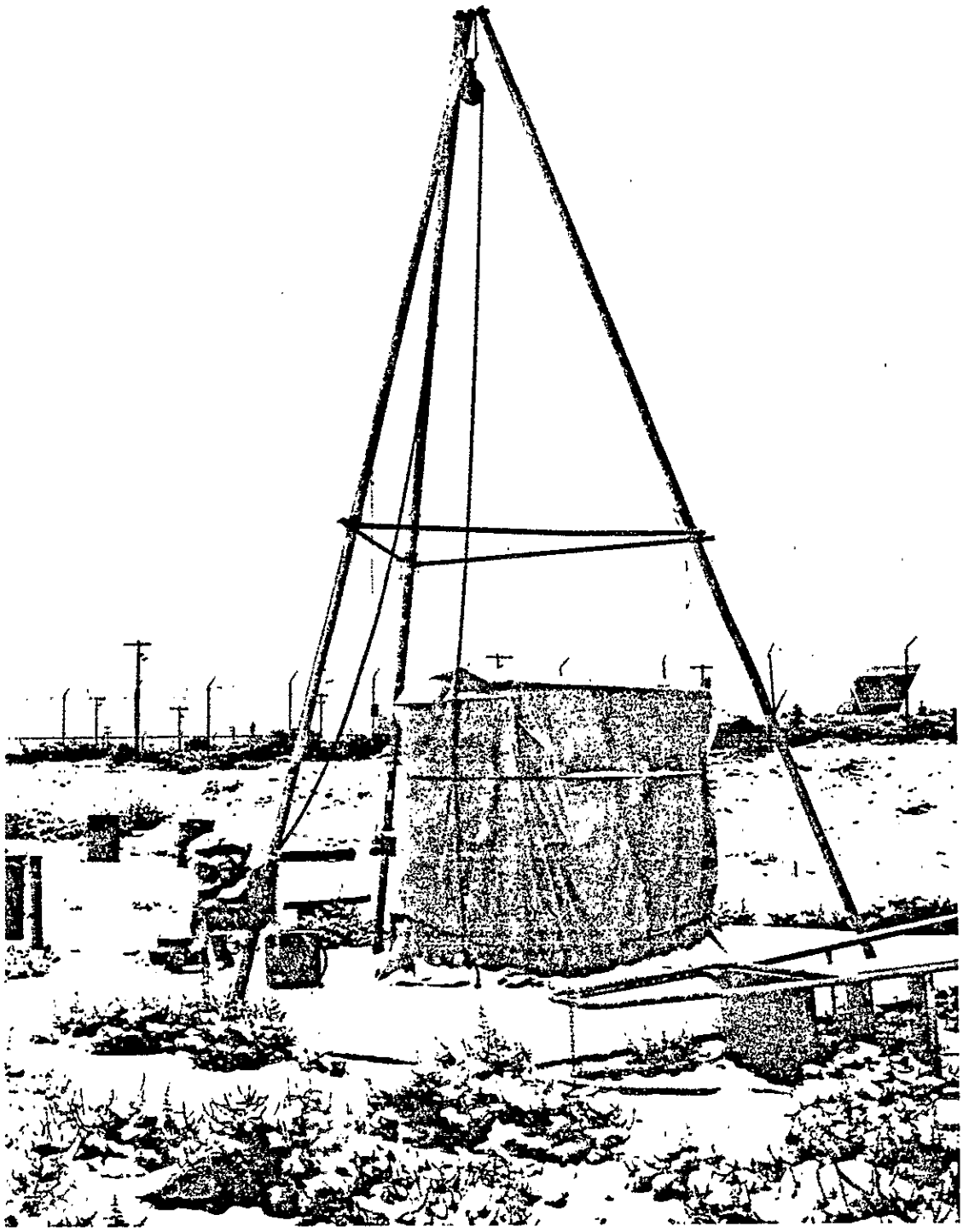


FIGURE 16. Tripod Drilling Rig and Glovebox.

TABLE 7. Analytical Results for Well 299-W18-75.

Depth [m (ft)]	^{239}Pu (nCi/g)	^{241}Am (nCi/g)
6.25 (20 ft 6 in.)	$<4.00 \times 10^{2}$	$1.06 \times 10^{2} \pm 1.48 \times 10^{-1}$
6.32 (20 ft 9 in.)	$<3.76 \times 10^{2}$	$9.24 \times 10^{1} \pm 1.29 \times 10^{-1}$
6.40 (21 ft 0 in.)	$<2.35 \times 10^{2} \pm 6.58 \times 10^{1}$	$1.24 \times 10^{2} \pm 1.61 \times 10^{-1}$
6.48 (21 ft 3 in.)	$3.18 \times 10^{2} \pm 7.00 \times 10^{1}$	$1.24 \times 10^{2} \pm 1.61 \times 10^{-1}$
6.55 (21 ft 6 in.)	$5.82 \times 10^{2} \pm 8.73 \times 10^{1}$	$2.24 \times 10^{2} \pm 2.91 \times 10^{-1}$
6.63 (21 ft 9 in.)	$5.24 \times 10^{2} \pm 8.38 \times 10^{1}$	$2.05 \times 10^{2} \pm 2.66 \times 10^{-1}$
6.71 (22 ft 0 in.)	$1.06 \times 10^{3} \pm 1.17 \times 10^{2}$	$2.41 \times 10^{2} \pm 2.89 \times 10^{-1}$
6.78 (22 ft 3 in.)	$<4.06 \times 10^{1}$	$3.41 \times 10^{0} \pm 1.40 \times 10^{-2}$
6.81 (22 ft 4 in.)	$8.24 \times 10^{2} \pm 1.48 \times 10^{2}$	$2.76 \times 10^{2} \pm 3.59 \times 10^{-1}$
6.88 (22 ft 7 in.)	$6.71 \times 10^{2} \pm 1.41 \times 10^{2}$	$2.69 \times 10^{2} \pm 3.50 \times 10^{-1}$
6.96 (22 ft 10 in.)	$6.41 \times 10^{2} \pm 1.03 \times 10^{2}$	$1.76 \times 10^{2} \pm 2.46 \times 10^{-1}$
7.04 (23 ft 1 in.)	$6.12 \times 10^{1} \pm 1.16 \times 10^{1}$	$1.92 \times 10^{2} \pm 2.69 \times 10^{-1}$
7.11 (23 ft 4 in.)	$6.71 \times 10^{1} \pm 1.14 \times 10^{1}$	$3.65 \times 10^{0} \pm 1.50 \times 10^{-2}$
7.19 (23 ft 7 in.)	$<5.06 \times 10^{1}$	$3.65 \times 10^{0} \pm 1.50 \times 10^{-2}$
7.24 (23 ft 9 in.)	$5.65 \times 10^{2} \pm 6.78 \times 10^{1}$	$6.88 \times 10^{1} \pm 1.31 \times 10^{-1}$
7.47 (24 ft 6 in.)	$<4.12 \times 10^{1}$	$3.62 \times 10^{0} \pm 1.48 \times 10^{-2}$
7.54 (24 ft 9 in.)	$<1.53 \times 10^{1}$	$6.88 \times 10^{1} \pm 6.40 \times 10^{-1}$
7.62 (25 ft 0 in.)	$2.40 \times 10^{2} \pm 2.38 \times 10^{1}$	$2.76 \times 10^{1} \pm 4.69 \times 10^{-2}$
7.70 (25 ft 3 in.)	$<3.59 \times 10^{1}$	$4.88 \times 10^{0} \pm 1.71 \times 10^{-2}$
7.77 (25 ft 6 in.)	$<1.00 \times 10^{2}$	$1.27 \times 10^{1} \pm 4.83 \times 10^{-2}$
7.85 (25 ft 9 in.)	$<5.88 \times 10^{1}$	$3.53 \times 10^{-1} \pm 4.87 \times 10^{-3}$
8.00 (26 ft 3 in.)	$<2.82 \times 10^{1}$	$4.06 \times 10^{-1} \pm 4.87 \times 10^{-3}$
8.08 (26 ft 6 in.)	$7.12 \times 10^{1} \pm 1.21 \times 10^{1}$	$3.62 \times 10^{0} \pm 1.48 \times 10^{-2}$
8.25 (27 ft 1 in.)	$5.86 \times 10^{2} \pm 7.62 \times 10^{1}$	$1.59 \times 10^{2} \pm 2.23 \times 10^{-1}$
8.74 (28 ft 8 in.)	$4.93 \times 10^{2} \pm 5.92 \times 10^{1}$	$1.32 \times 10^{2} \pm 1.72 \times 10^{-1}$
9.17 (30 ft 1 in.)	$1.52 \times 10^{2} \pm 3.04 \times 10^{1}$	$2.29 \times 10^{1} \pm 7.10 \times 10^{-2}$
9.63 (31 ft 7 in.)	$<7.60 \times 10^{1}$	$7.53 \times 10^{0} \pm 3.46 \times 10^{-2}$
10.34 (33 ft 11 in.)	$<6.50 \times 10^{1}$	$3.71 \times 10^{0} \pm 2.45 \times 10^{-2}$
10.67 (35 ft 0 in.)	$<1.59 \times 10^{0}$	$2.53 \times 10^{-2} \pm 2.43 \times 10^{-4}$
11.07 (36 ft 4 in.)	$<1.76 \times 10^{0}$	$1.59 \times 10^{-2} \pm 2.23 \times 10^{-4}$
11.48 (77 ft 8 in.)	$<1.55 \times 10^{0}$	$8.82 \times 10^{-3} \pm 1.50 \times 10^{-4}$
11.48 (37 ft 8 in.)	$4.92 \times 10^{-3} \pm 2.40 \times 10^{-4}$[a]	--
11.76 (38 ft 7 in.)	$2.17 \times 10^{-3} \pm 1.30 \times 10^{-4}$[a]	--
12.22 (40 ft 1 in.)	$1.30 \times 10^{-3} \pm 6.50 \times 10^{-5}$[a]	--
12.57 (41 ft 3 in.)	$4.11 \times 10^{-3} \pm 2.06 \times 10^{-4}$[a]	--
12.95 (42 ft 6 in.)	$3.52 \times 10^{-4} \pm 3.17 \times 10^{-5}$[a]	--

[a]Results were obtained from Alpha Energy Analysis.

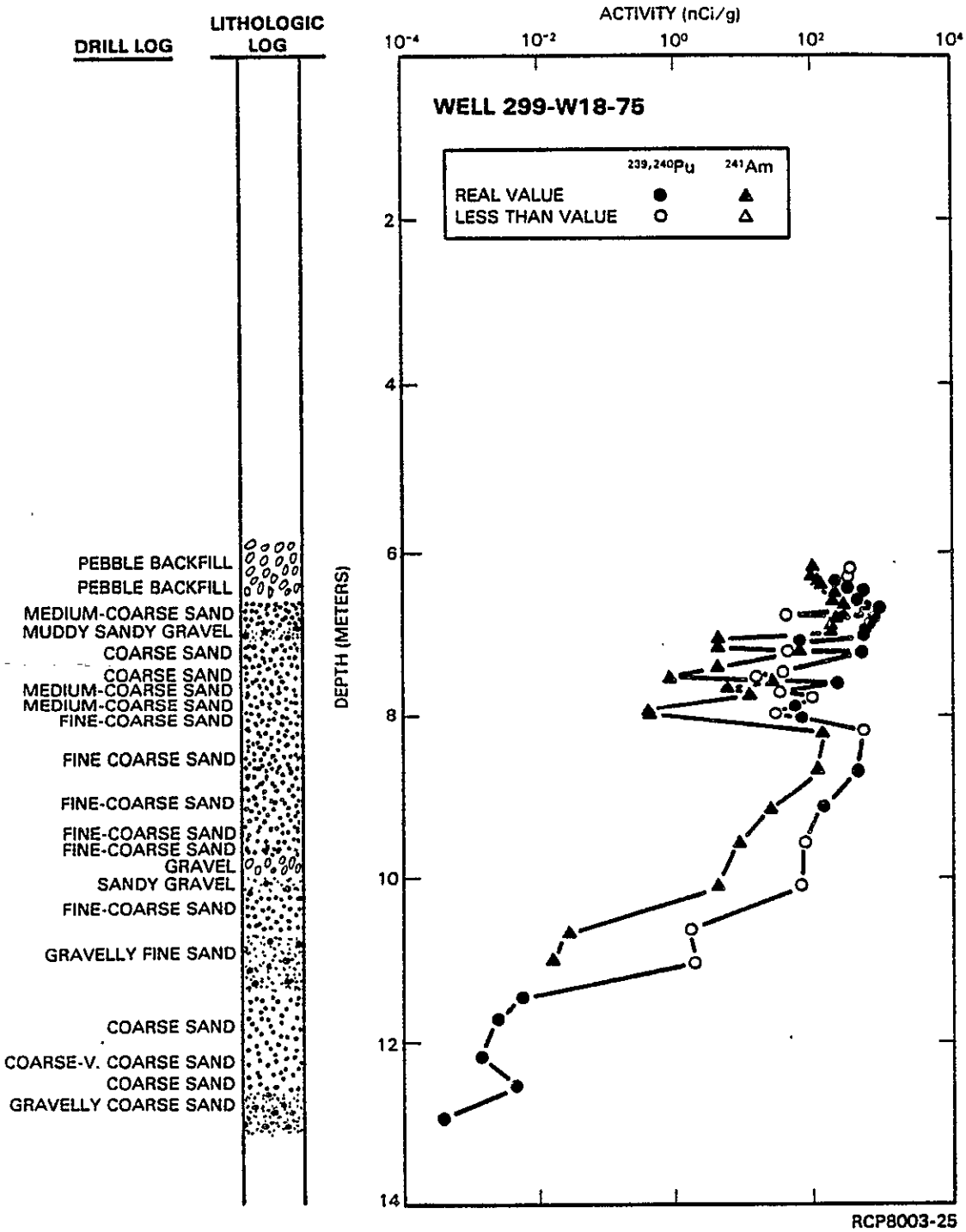


FIGURE 17. Drill Log and Activity Profile for Well 299-W18-75 Drilled in 1976.

(32.8 ft) from ground surface. Below a depth of 10 m (32.8 ft), the activity quickly dropped to picocurie levels, as indicated by the results reported for the five samples analyzed for plutonium using alpha energy analysis.

Finally, the plutonium and americium concentrations appeared to vary sympathetically, suggesting that the americium activity resulted from in situ decay of ^{241}Pu.

Three wells (152, 153, and 157) were drilled in 1976 at the perimeter of the crib to depths of approximately 35 m (115 ft). Portable radiation survey instruments detected no contamination in any of the wells. Selected sediment samples from Wells 152 and 153 were sent for AEA. The results of the analyses are reported in Table 8 and suggest the following observation.

There was very little dispersion of plutonium away from the crib. All reported concentrations were less than 1 nCi/g, and in general were below 1 pCi/g (10^{-3} nCi/g). Higher levels of activity observed in two of the samples at 7.62 m (25 ft) in Well 152 and 6.4 m (21 ft) in Well 153 probably resulted from the lateral spread of the waste from the crib bottom. One sample from a depth of 34.3 m (112.5 ft) in Well 152 had a reported activity of 20 pCi/g. Since nearby samples showed no increased activity, the results suggest some concentration mechanism was operating at this location, such as a silt lens with a higher sorption capacity. Insufficient data were available, however, for any additional interpretation.

Well 162 was drilled using the dual-wall core-barrel technique to provide an access for pulsed neutron source measurement equipment used to assess the degree of subcriticality. The results of the pulsed neutron measurements indicated that the returned signal was barely above instrumental background and thus there was no appreciable activity (Bierman, 1976). The value of K_{eff} is a measure of a systems approach to criticality, the ability to support a self-sustaining nuclear reaction. A value of K_{eff} = 1.0 indicates the system is critical. Values for K_{eff} less than one indicate the system is subcritical. The value of K_{eff}, for Well 162 was estimated to be less than 0.5. Application of the

TABLE 8. Analytical Results for Wells 299-W18-152 and 299-W18-153.

Depth [m (ft)]	^{239}Pu nCi/g of soil
Well 299-W18-152	
4.27 (14)	$8.00 \times 10^{-4} \pm 5.50 \times 10^{-5}$
7.62 (25)	2.25×10^{-2}
10.06 (33)	$4.23 \times 10^{-4} \pm 5.63 \times 10^{-5}$
13.41 (44)	$3.47 \times 10^{-4} \pm 3.12 \times 10^{-5}$
16.75 (55)	$3.83 \times 10^{-4} \pm 4.98 \times 10^{-5}$
21.34 (70)	$2.39 \times 10^{-3} \pm 1.67 \times 10^{-4}$
26.21 (86)	$8.38 \times 10^{-4} \pm 7.54 \times 10^{-5}$
29.87 (98)	$3.38 \times 10^{-4} \pm 4.73 \times 10^{-5}$
33.07 (108.5)	$9.23 \times 10^{-4} \pm 8.31 \times 10^{-5}$
34.29 (112.5)	$2.34 \times 10^{-2} \pm 3.98 \times 10^{-3}$
Well 299-W18-153	
6.4 (21)	1.18×10^{-1}
9.1 (30)	$4.28 \times 10^{-3} \pm 3.00 \times 10^{-4}$
12.2 (40)	1.16×10^{-3}
15.2 (50)	$5.41 \times 10^{-4} \pm 3.78 \times 10^{-5}$
18.3 (60)	$1.13 \times 10^{-3} \pm 1.01 \times 10^{-4}$
24.4 (80)	$2.03 \times 10^{-4} \pm 2.23 \times 10^{-5}$
26.8 (88)	$5.00 \times 10^{-4} \pm 3.00 \times 10^{-5}$
28.7 (94)	$4.50 \times 10^{-4} \pm 5.86 \times 10^{-5}$
31.7 (104)	$9.05 \times 10^{-4} \pm 5.43 \times 10^{-5}$
33.2 (109)	$4.37 \times 10^{-4} \pm 3.50 \times 10^{-5}$

appropriate theoretical criticality models used in data analysis was not amenable to a system this far subcritical, and further work was discontinued.

As part of the study to determine the K_{eff} of Well 162, the background neutron flux rate was measured (Figure 18). The neutron count rate was detectable above background in a single zone approximately 2.5 to 3.0 m (8 to 10 ft) thick. Activity peaked at 6.25 m (20.5 ft) from the top of the well casing or approximately 6.10 m (20 ft) below the ground surface, i.e., at a depth corresponding to the bottom of the crib. Without calibration of the neutron detector, it is impossible to convert the neutron flux to plutonium activity. Since the radius of interrogation for the neutron detector is unknown, it is also not possible to evaluate the actual thickness of the plutonium-contaminated layer. As a consequence, the results from this well cannot be quantitatively compared with the distribution observed with Well 75, where core samples were taken. The inner casing containing the sediment core from Well 162 was stored at the 216-Z-12 Crib and was sectioned during this study to obtain samples for use in the current investigation.

Routine Ground-Water Monitoring

A ground-water environmental surveillance monitoring network is maintained for the Hanford Site (Wheeler and Law, 1980; Eddy and Wilbur, 1980). Wells are sampled routinely. The samples are selectively analyzed for total alpha activity, total beta activity, several fission product radionuclides, uranium, and nitrate concentrations. The analytical results of the monitoring program are maintained as part of a permanent data base (Friendrichs, 1977).

Wells 2 and 5, drilled during the construction of the 216-Z-12 Crib, monitor the ground water beneath the site for radionuclide concentrations. The results of routine ground-water analyses from Wells 2 and 5 are summarized by Owens (1981) and are given in Table 9. Existing guidelines for plutonium and americium concentrations in ground water are 5 and 4 pCi/mL, respectively. The limit of detection for the total alpha detector system used is approximately 1.7×10^{-2} pCi/mL. No alpha

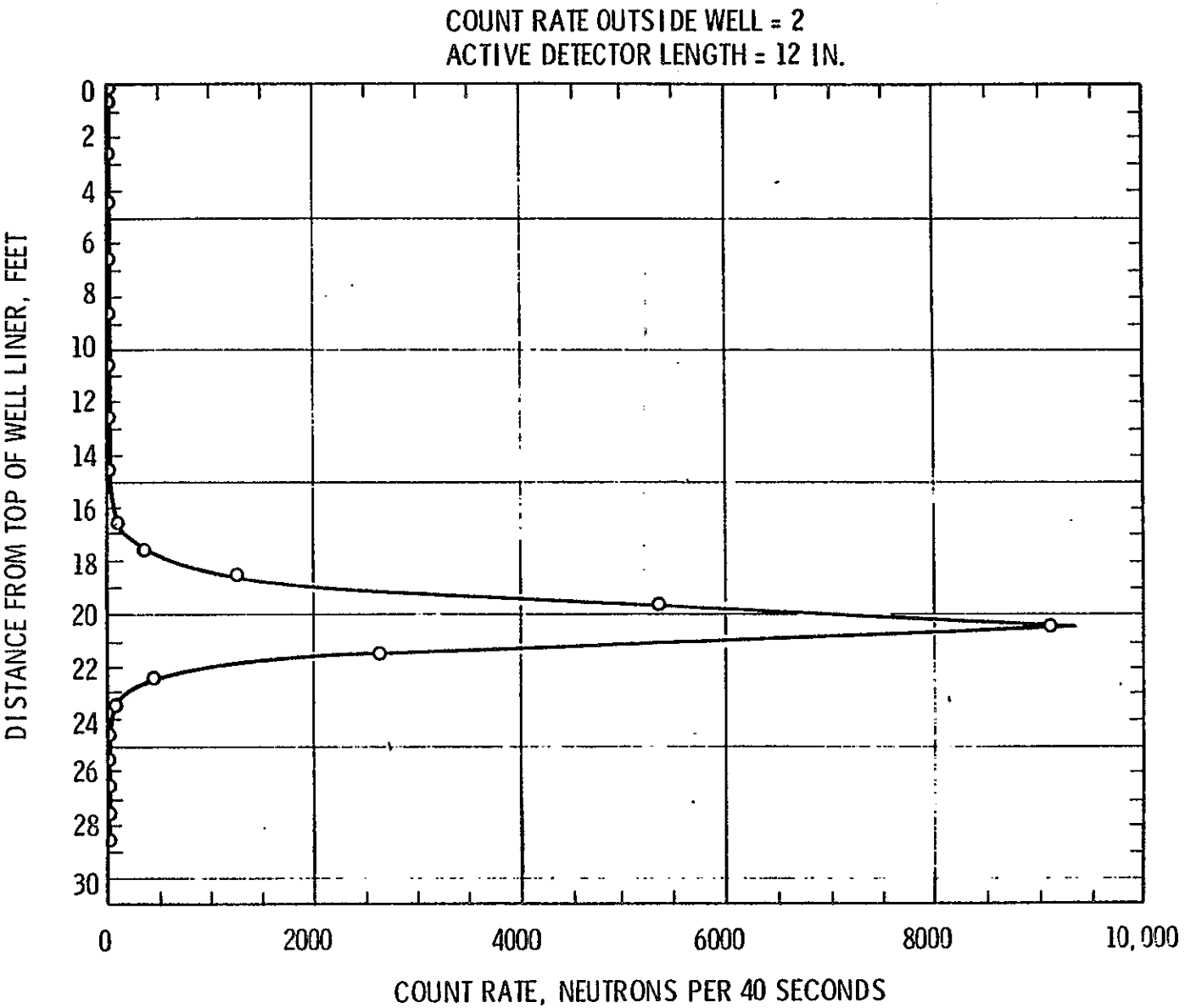


FIGURE 18. Neutron Count Rate as a Function of Depth in Well 299-W18-162, 216-Z-12 Crib (Subtract 6 in. to Get Distance From Ground Surface) (Bierman, 1976).

TABLE 9. Ground-Water Sample Results from Wells Monitoring 216-Z-12 Crib (Owens, 1981).[a]

Radionuclide[b] (pCi/mL)	Years sampled									
	1967	1969	1971	1972	1973	1974	1975	1976	1977	1978
Well 299-W18-2										
Total alpha	-	-	$<1.5 \times 10^{-2}$	$<1.5 \times 10^{-2}$	$<1.5 \times 10^{-2}$	$<1.5 \times 10^{-2}$	$<1.5 \times 10^{-2}$	$<1.7 \times 10^{-2}$	$<1.5 \times 10^{-2}$	-
Total beta	-	-	1.3×10^{-1}	1.4×10^{-1}	8.9×10^{-2}	7.4×10^{-2}	7.7×10^{-2}	7.9×10^{-2}	7.3×10^{-2}	-
Well 299-W18-5										
Total alpha	-	$<1.1 \times 10^{-2}$	$<1.4 \times 10^{-2}$	$<1.4 \times 10^{-2}$	$<1.4 \times 10^{-2}$	$<1.4 \times 10^{-2}$	$<1.4 \times 10^{-2}$	$<1.4 \times 10^{-2}$	$<1.4 \times 10^{-2}$	$<1.4 \times 10^{-2}$
Total beta	$3.7 \times 10^{+0}$	-	1.3×10^{-1}	1.9×10^{-1}	1.0×10^{-1}	7.6×10^{-2}	1.1×10^{-1}	7.3×10^{-2}	7.3×10^{-2}	7.3×10^{-2}
^{90}Sr	1.1×10^{-2}	-	-	-	-	-	-	-	-	-
^{3}H	-	-	-	-	$1.4 \times 10^{+1}$	$1.7 \times 10^{+1}$	$7.7 \times 10^{+0}$	$2.3 \times 10^{+0}$	-	-

[a] From Friendrichs, 1977.

[b] Some values are averages computed for the year.

activity was detected in any of the years reported. Breakthrough of measurable concentrations of plutonium or americium with the waste liquid to the ground water did not occur.

Photographing the Interior of the 241-Z-361 Settling Tank

In 1974, the liquid contents of the 241-Z-361 Settling Tank were removed. Two solution samples were analyzed for plutonium content. Analysis showed plutonium and americium concentrations of 120,000 and 43,000 pCi/mL, respectively. The solution was reported as having a pH of 6 and a specific gravity of 1.001. The reported plutonium and americium concentrations are approximately 100 and 50 times higher respectively than concentrations reported by Reisenauer (1959) for the waste streams being discharged to the settling tank (see the "Previous Laboratory Studies" section). Plutonium concentrations in the settling tank, however, may have been buffered by the sludge and may not have been representative of the plutonium in solution entering the tank.

After the liquid contents were removed, a camera was lowered through the south manhole (see Figure 11) to photograph the tank's interior. Figure 19 is a photomosaic prepared from the pictures. The view is looking toward the inlet end of the tank. The baffle over the inlet pipes is visible at the opposite end although the bottom portion has corroded away. The overflow level is marked clearly as a ring of material around the side of the tank. The remaining particulate material (sludge) is visible on the bottom of the tank with a shallow layer of solution remaining at the left. The 2-in. liquid-level well is clearly visible to the left side of the tank but the 8-in. monitoring well has corroded away and only a stump is visible in the lower left corner at the level of the remaining solution. What appears to be an organic film or 'skin' is observed to be hanging from the side walls at several locations around the tank. Bulk organic liquids were discharged to the high-salt cribs as previously discussed. However, an appreciable quantity of organic liquid apparently reached the settling tank to form the observed film.

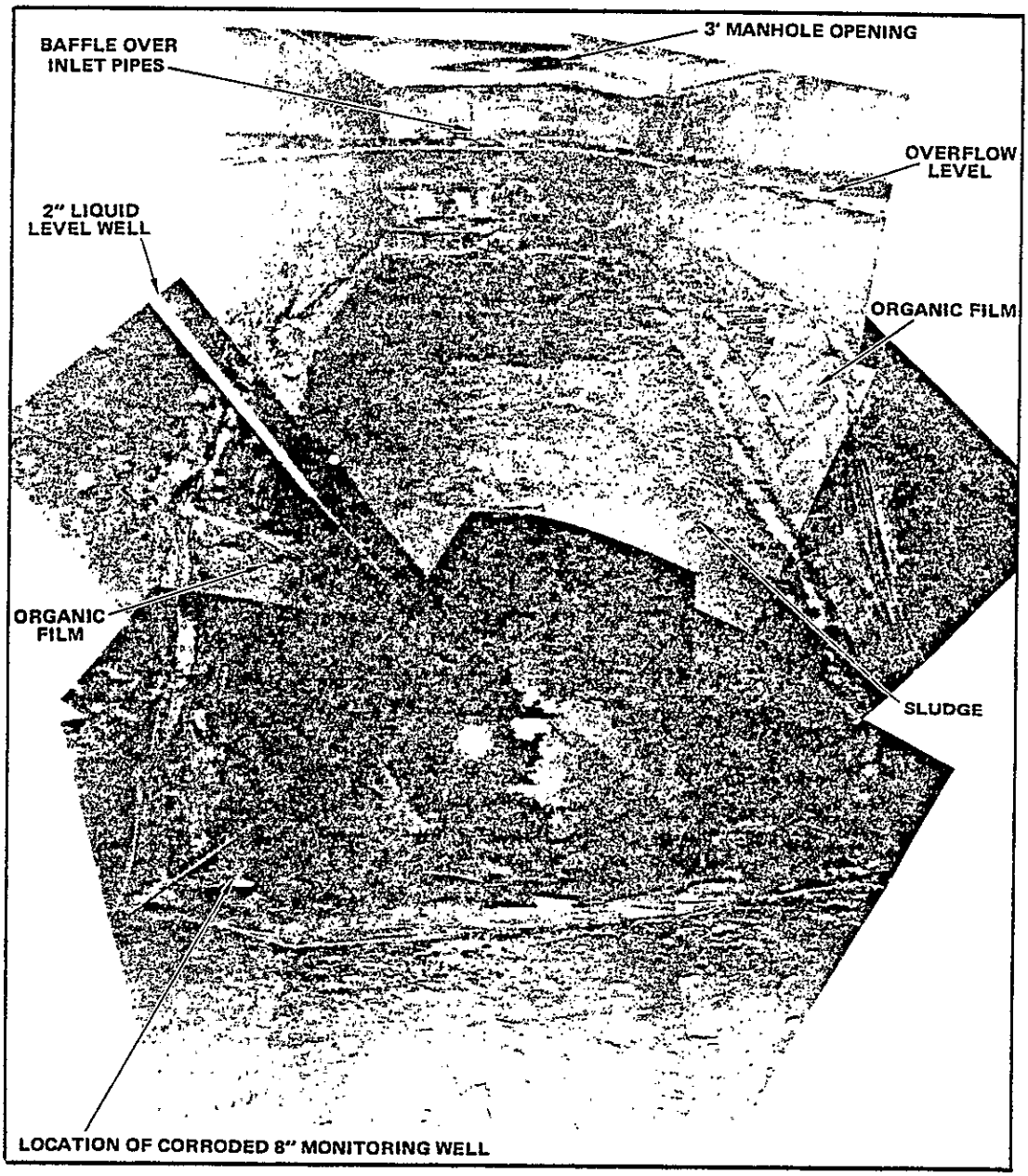


FIGURE 19. Photomosaic of the Interior of the 241-Z-361 Settling Tank.

PREVIOUS LABORATORY STUDIES

A single laboratory study directly concerned with the 216-Z-12 Crib has been conducted. This study (Reisenauer, 1959) investigated the breakthrough characteristics of radionuclides in several waste types for Hanford sediments. For the 216-Z-12 Crib, four short soil columns (1.9 by 20 cm) were prepared. The waste solution used in the study was a sample collected from the 216-Z-12 Waste Stream with a composition representative of average waste. The waste solution was identified as having 93 pCi/mL of ^{239}Pu and 101 pCi/mL of americium.* The solution was passed through the column at a rate of 1.43 mL/cm^2/hr. No breakthrough was observed after 100 column volumes of solution. Reisenauer (1959) noted:

> "In extrapolating laboratory soil column data to the soil column beneath a disposal facility it is assumed that the 'field column volume' is that directly under the crib, having the same areas as the liquid surface in the crib and with a length equal to the depth of the local water table. This calculation, therefore, does not consider any lateral spreading of the waste in the ground. The laboratory determination of crib capacity will thus be conservative."

For the 216-Z-12 Crib, a column volume was 3.23×10^7 L (6.1 m x 91.4 m x 57.9 m x 10^3 L/m^3). Approximately nine column volumes (2.8×10^8 L/ 3.2×10^7 L/col:vol) of waste were discharged to the 216-Z-12 Crib. As a result, the liquid phase of the discharged waste reached the ground water beneath the crib. The experiments indicate that no detectable concentration of plutonium or americium would remain in the liquid phase as a result of waste-sediment interactions.

It is interesting to note that the americium activity in the waste solution reported by Reisenauer differed from what was previously reported on the sources of waste to the crib. The reported americium activity also was inconsistent with the results of this study, which indicate

*A report by Wood (1958) indicated that the average plutonium concentration of low-salt waste in 1957, before use of the 216-Z-12 Crib, was 800 pCi/mL.

that most of the americium in the crib could be accounted for by the beta decay of ^{241}Pu discharged in the waste. A satisfactory explanation for this discrepancy was not obtained.

CURRENT STUDY

The major objective of the current study, initiated in 1979, was to determine the general pattern of plutonium distribution at a level of 10,000 pCi/g of sediment (10 nCi/g) or greater in the sediments beneath the 216-Z-12 Crib. This information would provide the required input for current engineering evaluation of alternatives for the ultimate disposal of the transuranic-contaminated sediments. The existing data base (Kasper, 1981) for the 216-Z-12 Crib indicated that plutonium activity greater than 10,000 pCi/g did not occur deeper than 3 m (9.8 ft) from the crib bottom, or 10 m (33 ft) from the ground surface. To meet the major objective, seven new wells (179 through 185) were drilled to a depth of approximately 12 m (40 ft). The positions for the wells were selected along two sections, A-A' and B-B', one parallel to the distributor pipe, the other perpendicular to it (Figure 20). The locations would take advantage of the data that could be obtained from existing Wells 75, 151 through 157, and 162. Study objectives did not include a detailed definition of the plutonium distribution throughout the crib, or the present extent of the entire waste plume as marked by the liquid phase of the waste. Such additional information would require the drilling of a large number of additional wells and was beyond the present study's scope.

One minor objective of the study was to evaluate the extent and level of plutonium activity between the crib and Diversion Box 2. To meet this objective, a new well (179, also used to determine the pattern of plutonium distribution along cross section B-B') was drilled, and an existing well (154, which had been drilled in 1978 until activity was first encountered) was deepened.

A second minor objective was to study the occurrence of plutonium activity on the order of a few picocuries per gram, observed in Wells 152 and 153 at a depth of approximately 30 m below ground surface. This objective was met by deepening Well 181 to a final depth of 42 m and obtaining additional analyses of selected sediment samples from Wells 152, 153, and 157. Since the available information indicated that plutonium

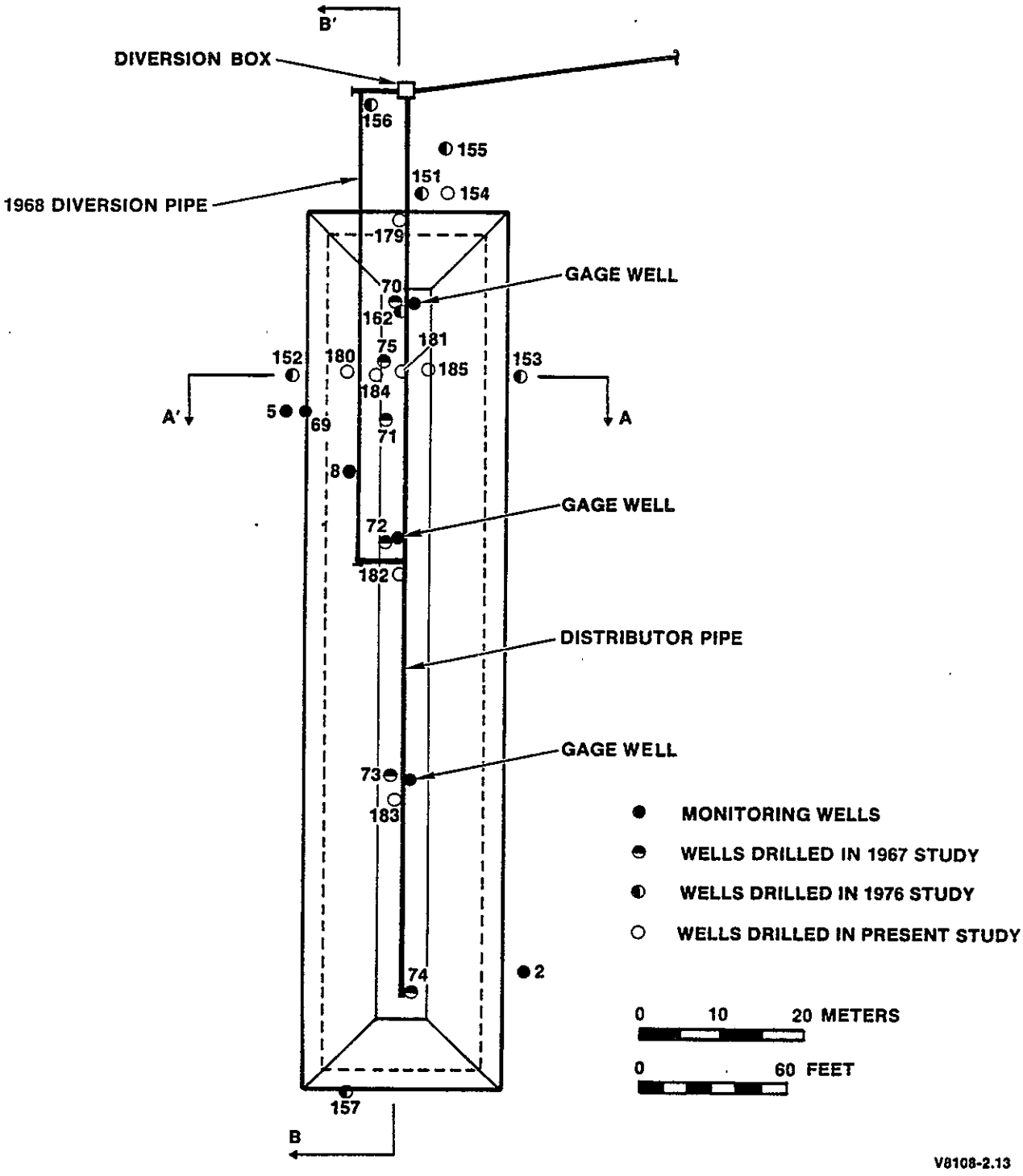


FIGURE 20. Well Locations.

in the waste solution was strongly sorbed onto the sediments within a few meters of the crib bottom, detectable activity at 30 m would suggest some mechanism for transporting plutonium in this waste to greater depths and some mechanism for removing the plutonium from solution at that depth. Although the liquid phase discharged to the crib reached the ground water, investigation of the waste plume to and in the ground water was not within the scope of the present study. As a consequence, Well 181 was only drilled to a depth of 42 m, 20 m above the water table. It is a general procedure to avoid drilling a well through a waste site and penetrating to the water table. The emplacement of the well disturbs the surrounding sediment and has been observed to provide a favorable migration pathway for the movement of moisture (Routson et al., 1979).

PRELIMINARY FIELD WORK

Although the two previous field studies (1968 and 1976) provided information on the distribution of the waste, they did not delineate or characterize the lateral spread of the waste away from the crib, and provided no information concerning the distribution of waste in the southern two-thirds of the crib after the 1968 diversion of the waste distribution line. This information would aid in planning the location of wells to be used in delineating the distribution of transuranic elements beneath the crib. Although additional data on the lateral distribution of waste was unavailable without drilling new wells, use of the "copper foil" technique was possible in existing wells in the southern two-thirds of the crib.

The copper foil technique is a method for the in situ determination of transuranic elements (Brodzinski, 1979). In this technique, the copper foil used is actually a copper plate, approximately 5 by 15 by 0.5 cm, and weighing approximately 200 g. When the foil is placed in the neutron flux generated by transuranic elements, the reaction $^{63}Cu(n,\gamma)^{64}Cu$ occurs. After the proper exposure (approximately 12 hr), the plate is removed and the activity of the gamma-ray-emitting ^{64}Cu ($t_{1/2}$ = 12.7 hr) in the metal is determined with multidimensional

NaI(Tl) counting equipment. With proper calibration, the transuranic content can be determined. The foils are sensitive to neutrons produced within about a meter and thus provide a weighted average of the transuranic content within a sphere having a 1-m radius, corresponding to a soil volume of interrogation of approximately 4,000 L.

Six copper foils were used in 1980. The first three foils were to be placed at 6.71 m (22 ft) in Wells 72, 73, and 74. Based on the information obtained from Well 75, if transuranic elements were present, the foils would be located in the volume of highest neutron flux. It was found, however, that Well 73 had filled in to a depth of 5.03 m (16.5 ft), and Well 74 to a depth of 5.79 m (19 ft). Since the foil method has a radius of interrogation of approximately 1 m, the foil in Well 73 was located too far above the level where activity was anticipated to detect it. Since Well 74 did not fill in as much as Well 73, any activity, if present, should have been detected. The results obtained by these three foils are reported in Figure 21. Failure to detect any activity in Well 74 suggested that the waste did not reach the end of the distributor pipe.

Three additional copper foils were used to attempt to resolve the question resulting from Well 73 filling in. A foil was placed in each of the two gauge wells near Wells 72 and 73. The third foil was placed in the vent at the intersection with the distributor pipe (see Figure 21). In the gauge wells, the foils are resting on top of the concrete pad on the crib bottom (see Figure 9). Since the aggregate used to line the bottom of the crib was not expected to retain significant amounts of activity, the activity detected would only be in the lower hemisphere of the volume of interrogation, but the concentration calculated would be averaged for the entire sphere. Thus, the results reported for the northern gauge well were lower than for the nearby well (72), but were comparable when the dilution factor was considered. The southern gauge well was found to have detectable levels of activity, but significantly less than that measured at the head of the diversion line. This suggests that the discharge of waste to the sediments stopped within a few meters of Well 73 and the southern gauge well, supporting

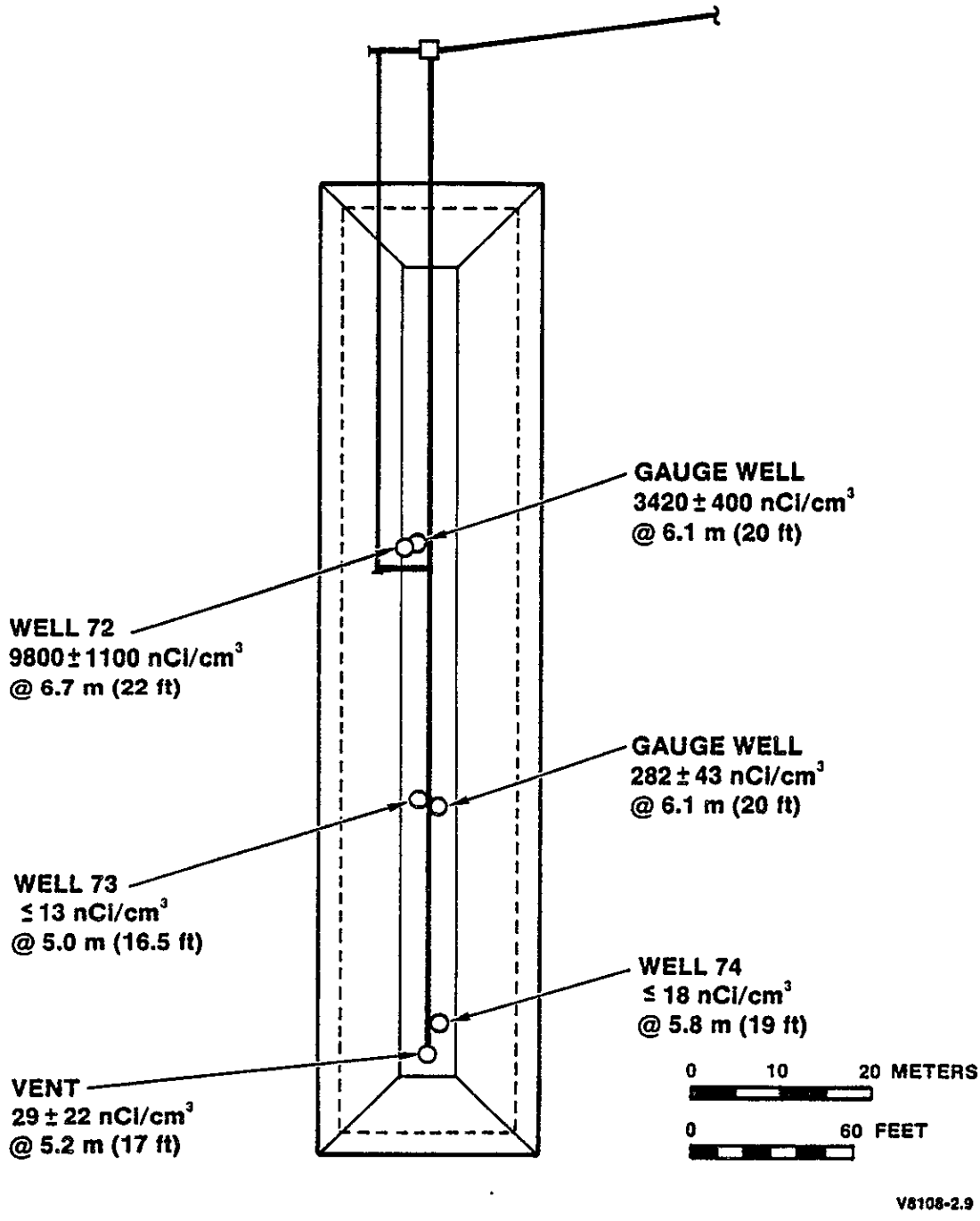


FIGURE 21. Analytical Results from Copper Foil Measurements.

the results from Well 74 and suggesting that no waste was discharged at the end of the crib.

METHODOLOGY

The general approach of the investigation was to drill wells in and around the 216-Z-12 Crib. The wells were drilled using specialized techniques and procedures developed at the Hanford Site. These techniques allow radioactively contaminated sediment to be obtained from liquid waste disposal sites without cross contaminating samples or releasing radioactive material to the environment. Selected samples from each well were collected throughout the sediment column for analysis of sediment size distribution, moisture content, and plutonium and americium activity. Analytical results determined the distribution of plutonium and americium with depth in the individual wells and then to interpret the distribution beneath the crib.

Well Drilling and Sampling

The wells were drilled using a cable tool drilling rig and either a drive barrel sampler or a dual-wall core-barrel sampler. The drive barrel sampler was used in locations where no alpha activity was anticipated. The dual-wall core-barrel was used to drill through the plutonium-contaminated sediment immediately below the crib bottom.

Drive Barrel Sampler. Use of a drive barrel sampler and a cable tool drilling rig is standard practice for drilling wells in unconsolidated or semiconsolidated sediments (Price et al., 1979). The sampler consists of a steel pipe approximately 0.5 m long, open on one end and welded to an adapter on the other to allow attachment to the weights ("jars") on the drilling rig. During drilling, the weights are raised and dropped onto the sampler, driving it into the ground. The well is progressively deepened by alternating the driving of the sampler and a larger-diameter pipe called the casing. The casing prevents collapse of the borehole. Throughout the entire operation, the depths of the casing and sample barrel are recorded before and after each successive drive in order to calculate what portion of the sample is the result of side wall sloughing.

Special procedures are required when drilling near disposal sites to prevent the release of any radioactive material encountered. As the sampler is withdrawn from the well, its outer surface is surveyed for radioactivity with portable radiation survey instruments. If no contamination is detected on the surface of the sampler, the sediment in the lower 25 cm of the sampler is emptied into a plastic sample bag, spread out in the bag, and surveyed again. If no radioactivity is detected, samples are collected for analysis and storage. A description of the sample is also recorded in the drill log to provide semiquantitative information on the sediment type. Samples are collected at approximately 1.5-m increments, or at each lithology change. The remaining sediments in the sampler are then emptied in the same manner, surveyed, and packaged for disposal. If any contaminated sediment is detected, the material is packaged according to applicable requirements for handling and shipping of transuranic-contaminated material and placed in a separate radioactive material storage for later sampling under controlled conditions.

Dual-Wall Core-Barrel. The dual-wall core-barrel technique was developed to obtain samples from the most contaminated sediments beneath the retired liquid waste disposal sites without releasing contamination to the environment. The technique uses the cable tool drilling rig to drive the sampler and recover the sediment core. The sampler consists of an inner and outer tube (approximately 3 m long), which attaches to a special drilling shoe and the driving head (Figure 22). The steps in using the sampler are illustrated in Figure 23. In Step 1, the complete sampler is set up and lowered into the existing well. In Step 2, the sampler is driven approximately 3 m deeper into the ground. In Step 3, the driving head is removed and the inner tube is removed (Figure 24). If deeper penetration is required with the sampler, a new inner tube is inserted into the well and another pair of inner and outer tubes are attached to the first two sections. The sampler is then driven another 3 m and the process is repeated. Once the volume of contamination has been penetrated, a drive barrel sampler can be used to penetrate deeper while the outer tube(s) act as the casing to support the well.

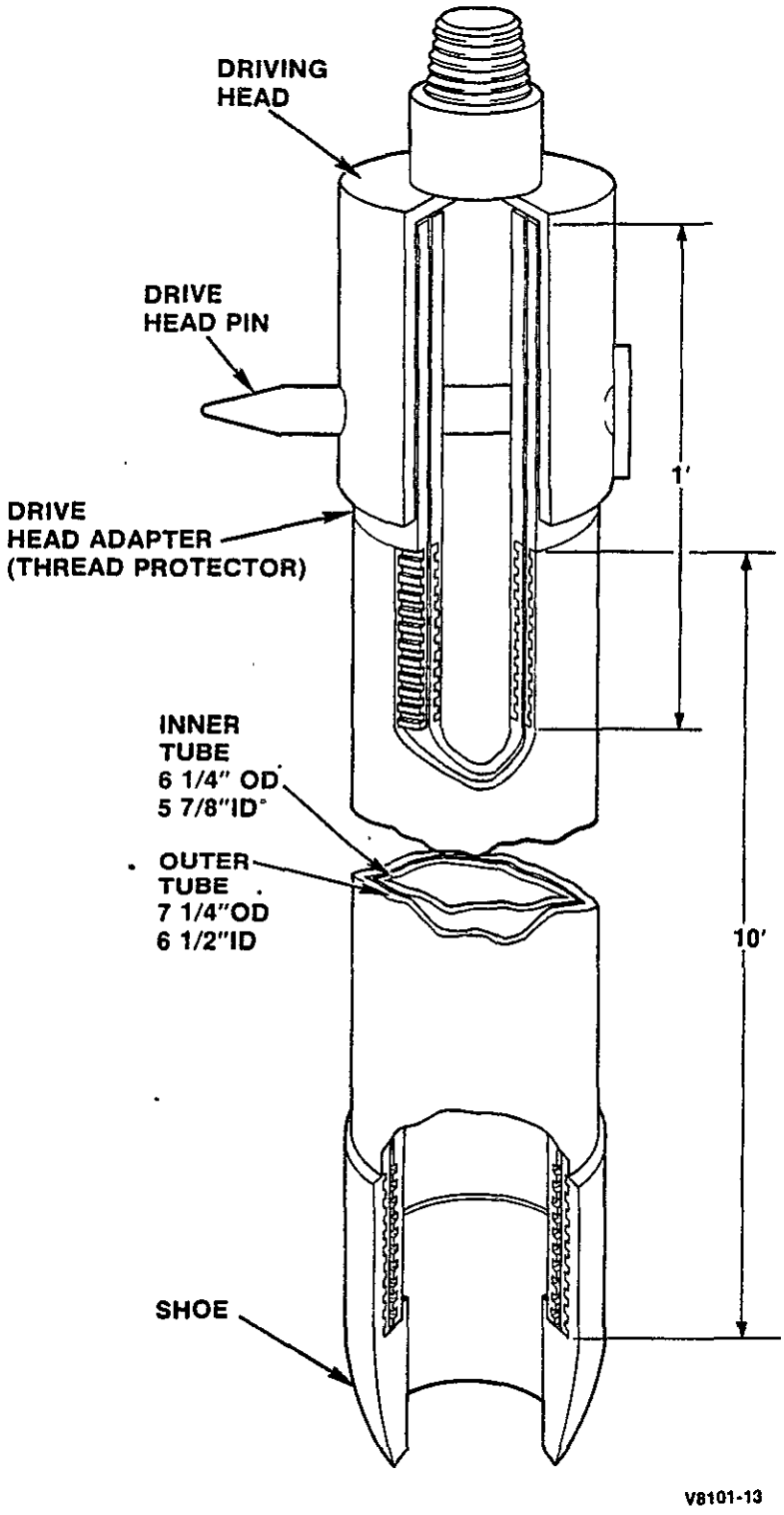


FIGURE 22. Dual-Wall Core-Barrel.

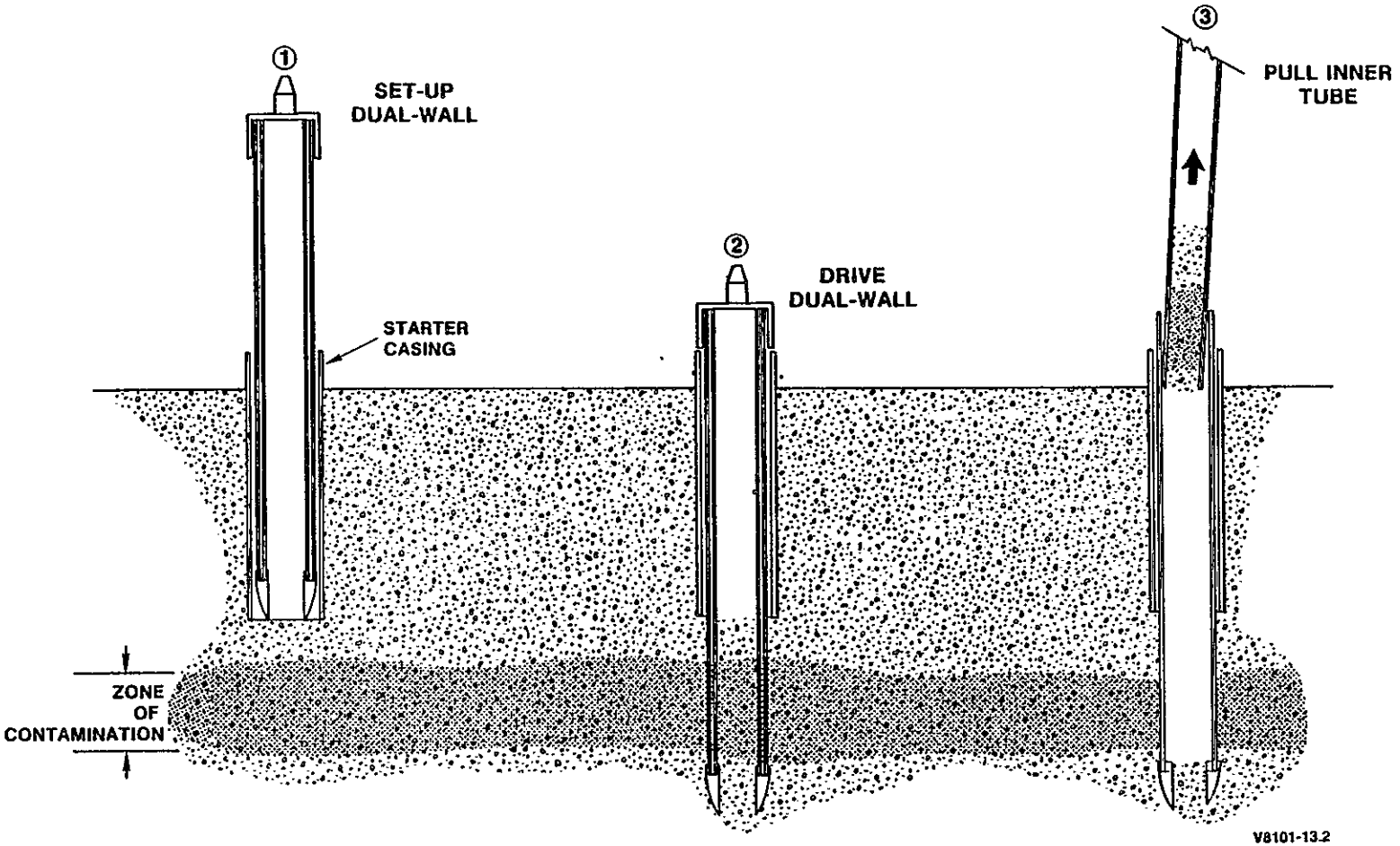


FIGURE 23. Procedure for Using the Dual-Wall Core-Barrel.

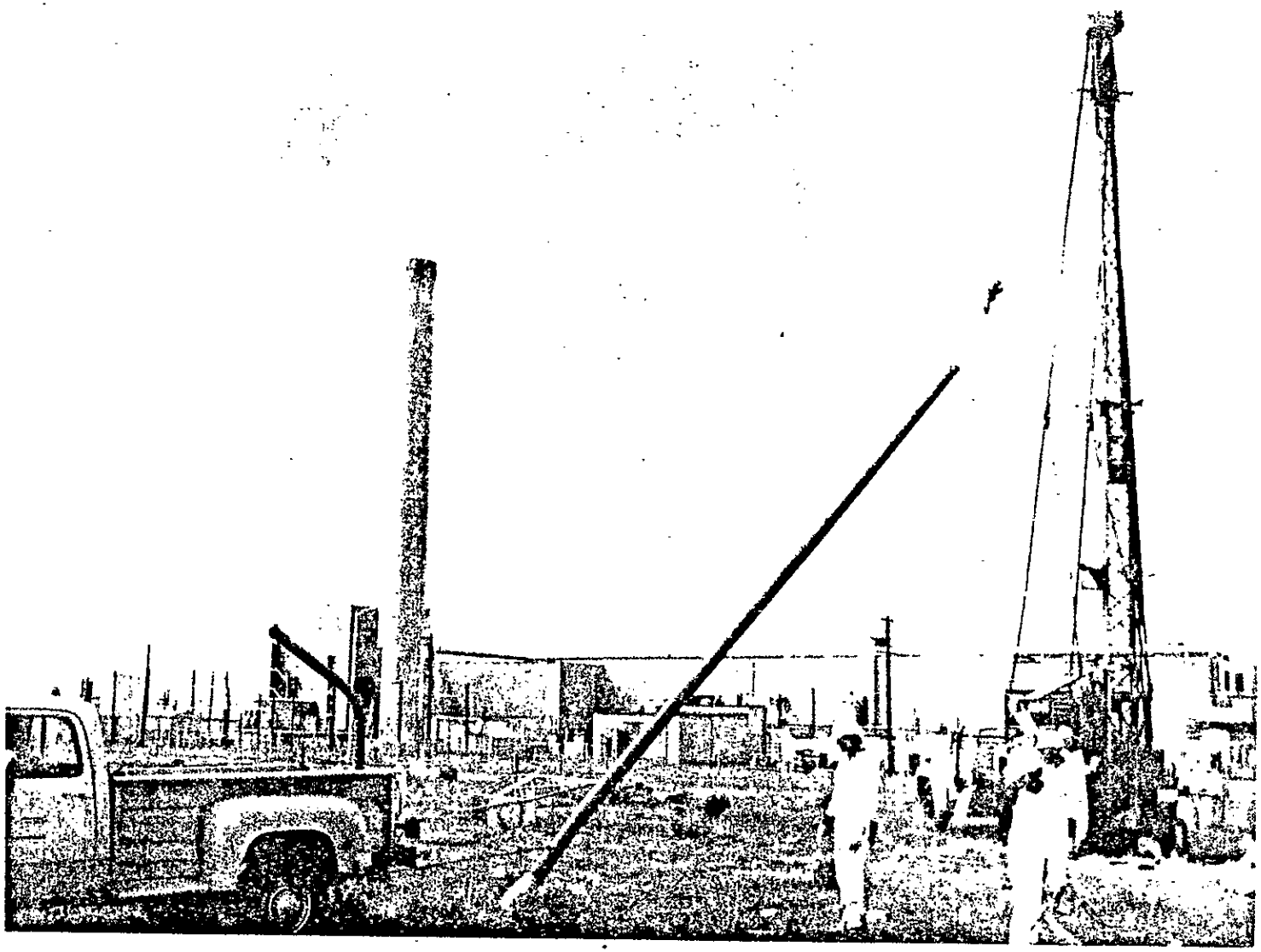


FIGURE 24. Removing Inner Tube of Dual-Wall Core-Barrel.

The inner tube containing the sediment core is stored for later sampling to permit quicker completion of the drilling. For sampling of the sediment from the inner tube, the core is moved to a building where special controls are set up to prevent the release and spread of radioactivity. The work is done in a small, plastic-walled box called a greenhouse, which is set up inside the permanent building. Negative air pressure is applied to the interior of the greenhouse by a fan through high efficiency particulate air filters to control airborne radioactivity. The end of the inner tube is inserted through a plastic sleeve in the wall of the greenhouse. The tube is supported to allow use of a pipe cutter to section the tube at selected locations (Figure 25). When the pipe is cut, the section is removed and the sediment exposed for sampling (Figure 26). Repeated cuts section the tube into lengths from 0.3 to approximately 1 m, depending upon the coverage desired. After the sediment samples are obtained, the sections are capped and placed into storage.

Analytical Techniques

Selected sediment samples were analyzed quantitatively for sediment size distribution, moisture content, and plutonium and americium concentrations to determine the geology and radionuclide distribution at the 216-Z-12 Site. The measurements made using portable radiation survey instruments provided only a qualitative measure of contamination and were used only as a guide for sample handling.

Granulometric Analysis. Uncontaminated sediment samples were dry-sieved using a nested sieve system that was mechanically shaken with a Rotap Shaker (Fecht and Price, 1977). Samples were sieved into seven size fractions (Table 10). During drilling operations, uncontaminated sediment samples were collected and stored in glass jars with a mouth diameter of approximately 7 cm. The amount of material greater than 7 cm was estimated at the time of the initial sampling and recorded in the well logs. The sediments retained on each sieve were weighed and recorded. Depending upon the weight percent of the various size fractions, the sediment samples were placed into 1 of 19 sediment classes

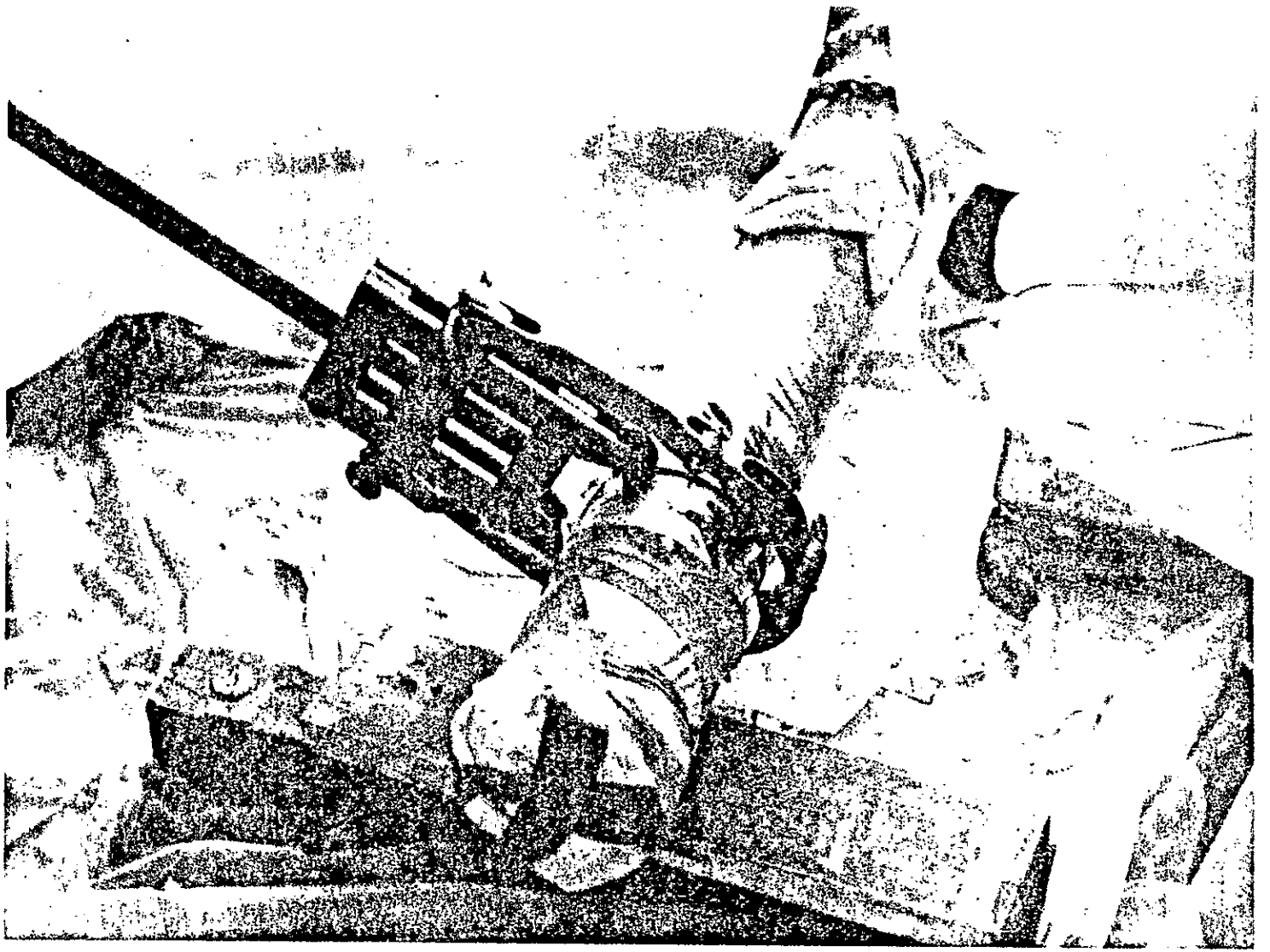


FIGURE 25. Sectioning Inner Tube.

FIGURE 26. Collecting Sediment Sample from Inner Tube.

shown in Figure 27, using the computer program ROC (Fecht and Price, 1977). The results are reported using an abbreviated sediment size notation. In the notation, the silt and clay size fraction is indicated by "m," the sand size fraction by "S," and gravel by "G." The major component in each sample is indicated by the last letter in the notation, and preceding letters, if present, are modifiers indicating additional components. Thus, "mS" indicates a silty sand, while "Sm" indicates a sandy silt or clay. A letter in parentheses indicates the fraction is modified by the term "slightly." Thus, "(m)S" indicates a slightly silty sand.

TABLE 10. Particle Size Nomenclature.*

Particle designation	Particle diameter (mm)
Gravel	8-2
Sand	
Very coarse	2-1
Coarse	1-0.5
Medium	0.5-0.25
Fine	0.25-0.125
Very fine	0.125-0.625
Silt (and clay)	<0.0625

*From Wentworth, 1922.

In addition to the major sediment classification, the sand classification is divided into five subdivisions according to the scheme given in Table 10. The subdivisions are indicated by a notation within a bracket, which modifies the sand, where

VC = very coarse
C = coarse
M = medium
F = fine
VF = very fine.

Thus (m)G[F-VF]S, would indicate a slightly silty, gravelly, fine to very fine sand.

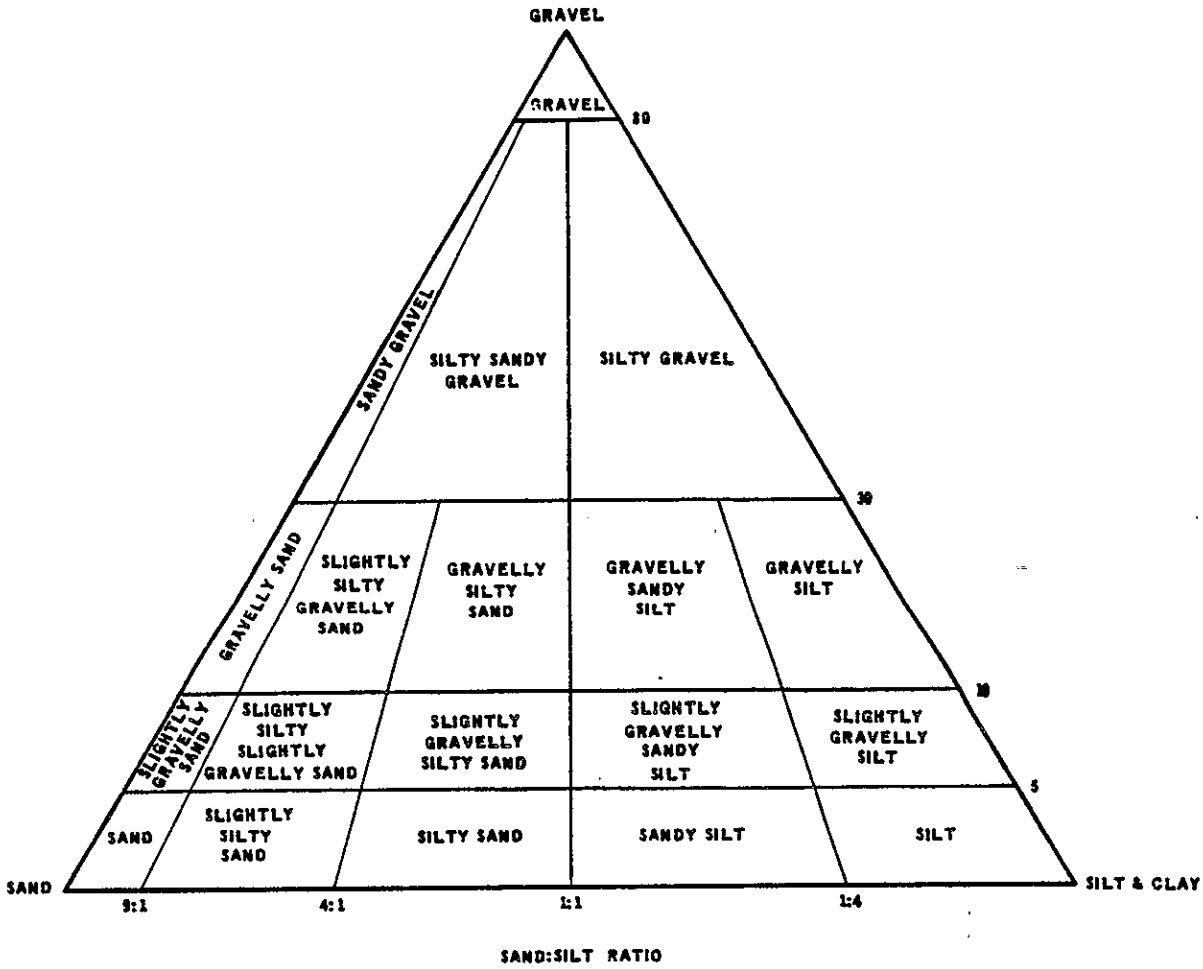


FIGURE 27. Sediment Classification (Folk, 1974).

Results of the granulometric analysis are presented in the "Results" section as part of the logs prepared for the individual wells. The information for each well was used to determine the sediment lithology for the 216-Z-12 Crib.

A technique for sieving radioactively contaminated sediments is available (Smith and Additon, 1980). During sampling of the dual-wall core-barrel, the plutonium-contaminated sediments were observed to have a reddish-brown coating, which in many cases cemented the grains into lithified fragments. Since the contaminated zone appeared to be present only in a single sand unit beneath the crib bottom, no additional information could be obtained by sieving the sediment, and the technique was not used.

X-Ray and Gamma Ray Energy Analysis. Aliquots of all sediment samples obtained during drilling were prepared for analysis of plutonium and americium content. All samples found to contain detectable alpha activity in the field, and most of the "uncontaminated" samples, were nondestructively analyzed using a lithium-drifted silicon [Si(Li)] detector system (Kay, 1980). Approximately 100-g aliquots of each sample were measured. The plutonium X-rays in the 17-keV region and the ^{241}Am gamma ray at 59.6 keV were counted using appropriate calibration standards. The system has a reported detection limit for plutonium of 2,000 pCi/g of sediment and for americium of approximately 200 pCi/g. Analytical results are reported in Appendix C.

To maintain confidence in the reported results from the Si(Li) detector system, duplicate or triplicate samples were used extensively to supplement the laboratory's own internal quality control standards. Except for a few samples with activity levels near the system's limit of detection, good agreement was obtained among aliquots. In addition, the results reported using the Si(Li) detector system were supplemented by the passive neutron logging discussed in a following section. The results indicated satisfactory confidence in the plutonium and americium results reported for the Si(Li) detector system, and in the interpretation of plutonium activity greater than 2,000 pCi/g and americium activity

greater than 200 pCi/g. This level of activity was sufficient to meet the major objective of the study, to define the limit of plutonium activity greater than 10,000 pCi/g.

Alpha Energy Analysis. To determine the plutonium and americium content of samples with activities below the limit of detection for the Si(Li) detector, transuranic concentrations were determined by AEA. The procedure required chemical digestion of the sediment using nitric acid-hydrofluoric acid, extraction and purification of the plutonium and americium, and electroplating the purified elements onto stainless steel planchettes (Major et al., 1971). The alpha particle energy spectrum was then counted using an alpha energy spectrometer.

Alpha energy analysis is the normally used procedure for determination of low levels of transuranic contamination. The detection limit for the alpha energy spectrometer is estimated as 0.02 ± 0.02 (1σ) pCi/analysis, or 0.002 ± 0.002 (1σ) pCi/g for a 10-g sample, assuming perfect recovery. Many factors result in an actual limit of detection for AEA being greater than the optimal value. Losses resulting from the digestion, chemical extraction, purification, and counting steps increase the detection limit. In addition, the confidence interval reported for an individual analysis is based solely on counting statistics and should not be taken as an estimate of the true sample variability. The variability of plutonium and americium in the original sediment sample and those introduced during sample selection and handling generally are regarded to be considerably larger. Based on experience with multiple analyses of 10-g duplicates for a well-characterized sample, a practical detection limit is estimated to be below 0.1 ± 0.1 (1σ) pCi/g. In this report, for evaluation of the distribution of plutonium and americium, 0.1 pCi/g was considered the lower limit of detection for the AEA system. Analyses were made for ^{238}Pu, $^{239,240}Pu$, and ^{241}Am. The detector system does not have the resolution to separate the ^{239}Pu and ^{240}Pu alpha energies and they are reported together. Eberline Instrument Corporation, Albuquerque, New Mexico (Eberline), and LFE Environmental Analysis Laboratory, Richmond, California (LFE) performed AEA. Results are reported in Appendix C.

Determination of plutonium activity less than 2,000 pCi/g and americium activity less than 200 pCi/g depended on AEA results. To supplement LFE's and Eberline's internal quality control programs and maintain confidence in the reported results, double blind standards and duplicate samples were used. The standard material was provided by the U.S. DOE Environmental Measurements Laboratory* (EML). The material was not considered a true standard, but what is known as a consensus standard or natural matrix standard. It is a mixture of soil collected at Oak Ridge National Laboratory† and the Savannah River Plant‡, and has been analyzed at least three times by 10 laboratories to determine the concentration. The estimated concentration of plutonium in the sediment reported by EML was 0.5 ± 0.05 pCi $^{239,240}Pu$/g and 0.027 ± 0.005 pCi ^{238}Pu/g. No value for ^{241}Am activity was reported.

Sixteen aliquots of the consensus standard were sent as double blind standards (9 to Eberline, 7 to LFE) in the batches of sediment samples to be analyzed. The results reported by both laboratories in Table 11 agree with the estimated concentrations reported by EML, and when evaluated with the results reported for duplicate sediment samples, provide satisfactory confidence in the determination of the plutonium and americium distribution.

Moisture Analysis. The moisture content of sediment samples collected during well drilling in the current study were measured by standard gravimetric procedures. After the level of activity was determined by portable radiation survey instruments, two samples, approximately 150 g each, were collected and placed in previously tared moisture cans. The cans were then capped and sealed with tape. The sealed cans were transferred to the laboratory where they were weighed and then dried at 105°C for 24 hours and then reweighed. The average of the two samples are reported in Appendix E in terms of weight percent moisture.

*U.S. DOE Environmental Measurements Laboratory, New York, New York.

†Oak Ridge National Laboratory, Oak Ridge, Tennessee.

‡Savannah River Plant, Savannah, Georgia.

TABLE 11. Reported Analytical Results for Consensus Standard.

^{238}Pu (pCi/g)*	^{239}Pu (pCi/g)*	^{241}Am (pCi/g)*
Eberline Instrument Corporation		
$7.95 \times 10^{-3} \pm 300.\%$	$3.42 \times 10^{-1} \pm 18.2\%$	$1.92 \times 10^{-1} \pm 30.8\%$
$3.03 \times 10^{-2} \pm 92.\%$	$6.24 \times 10^{-1} \pm 12.5\%$	$3.03 \times 10^{-1} \pm 20.2\%$
$1.49 \times 10^{-2} \pm 142.\%$	$4.70 \times 10^{-1} \pm 16.4\%$	$2.91 \times 10^{-1} \pm 21.1\%$
$8.52 \times 10^{-3} \pm 173.\%$	$6.22 \times 10^{-1} \pm 14.4\%$	$2.07 \times 10^{-1} \pm 25.8\%$
$3.72 \times 10^{-2} \pm 53.\%$	$6.99 \times 10^{-1} \pm 13.6\%$	$2.23 \times 10^{-1} \pm 14.3\%$
$8.60 \times 10^{-2} \pm 52.\%$	$6.50 \times 10^{-1} \pm 14.8\%$	$2.44 \times 10^{-1} \pm 21.4\%$
$1.57 \times 10^{-2} \pm 100.\%$	$4.86 \times 10^{-1} \pm 16.1\%$	$4.66 \times 10^{-1} \pm 29.3\%$
$2.75 \times 10^{-2} \pm 117.\%$	$4.74 \times 10^{-1} \pm 15.6\%$	$2.48 \times 10^{-1} \pm 18.2\%$
$-7.77 \times 10^{-3} \pm 332.\%$	$4.66 \times 10^{-1} \pm 15.2\%$	$2.84 \times 10^{-1} \pm 23.4\%$
Average		
$2.45 \times 10^{-2} \pm 109.\%$	$5.37 \times 10^{-1} \pm 21.6\%$	$2.49 \times 10^{-1} \pm 32.9\%$
LFE Environmental Analysis Laboratory		
$3.1 \times 10^{-2} \pm 12.9\%$	$4.86 \times 10^{-1} \pm 3.5\%$	$2.43 \times 10^{-1} \pm 6.6\%$
$2.0 \times 10^{-2} \pm 10.0\%$	$4.18 \times 10^{-1} \pm 3.1\%$	$1.94 \times 10^{-1} \pm 7.2\%$
$3.4 \times 10^{-2} \pm 8.8\%$	$5.96 \times 10^{-1} \pm 3.2\%$	$2.43 \times 10^{-1} \pm 4.9\%$
$2.6 \times 10^{-2} \pm 15.4\%$	$5.70 \times 10^{-1} \pm 3.3\%$	$2.62 \times 10^{-1} \pm 3.4\%$
$2.5 \times 10^{-2} \pm 12.0\%$	$5.17 \times 10^{-1} \pm 3.5\%$	$2.37 \times 10^{-1} \pm 3.8\%$
$2.2 \times 10^{-2} \pm 13.6\%$	$5.40 \times 10^{-1} \pm 3.7\%$	$2.59 \times 10^{-1} \pm 4.3\%$
$2.4 \times 10^{-2} \pm 12.5\%$	$5.81 \times 10^{-1} \pm 2.9\%$	$2.90 \times 10^{-1} \pm 6.9\%$
Average		
$2.6 \times 10^{-2} \pm 18.8\%$	$5.30 \times 10^{-1} \pm 11.7\%$	$2.47 \times 10^{-1} \pm 11.7\%$

*Plus or minus one standard deviation (1σ) reported as a percentage of the reported value.

Neutron Flux Measurements

Several techniques were used in this study that attempted to use measurement of the neutron flux to estimate the transuranic concentrations. The natural fissioning of ^{239}Pu, per se, produces neutrons. In addition, the alpha particles produced by the decay of both plutonium and americium interact with light elements (mainly oxygen and fluorine) to produce neutrons by (α,n) reactions. The (α,n) reactions produce most of the background neutron flux; the alpha decay of ^{241}Am comprises most of this contribution (Stokes et al., 1978). Because the neutron flux is produced from several transuranic sources and is affected by several factors, including moisture content, measurement of the natural background provides only a qualitative guide to transuranic distribution. The information, however, is useful in selecting samples for quantitative analyses, providing a continuous log of activity, and as an aid in determining the general distribution of plutonium and americium.

It is possible to induce the fissioning of plutonium and uranium by using a neutron source and to measure the neutrons produced by the fissioning. This procedure (active logging) allows direct determination of the plutonium concentration when proper calibration is obtained. Downhole probes that induce fissioning of ^{235}U have been developed for uranium exploration. These probes have been tested extensively in the 216-Z-1A Crib to evaluate their ability to measure plutonium in situ (Stokes et al., 1978, 1979; Barnard and Stephenson, 1980). One of the systems was on site during the 216-Z-12 Crib study and was used to log Well 181.

Passive Neutron Measurements. Two passive techniques were used to measure the neutron flux in the 216-Z-12 Crib. Logging of wells with a neutron detector was used to provide a quick survey of transuranic activity, and aid in sectioning the dual-wall inner tube and selecting samples. The copper foil technique, discussed in the "Preliminary Field Work for the Current Study" section, permitted measurement of the neutron flux at specific locations, but was not practical for logging a well.

Wells in the 216-Z-12 Crib were neutron logged with a ^{3}He neutron detector in a neutron moisture meter without the americium/ beryllium source. Passive logging previously was determined useful; it provided as much useful information during a test of one of the active neutron logging techniques on the distribution of transuranic elements with depth as did the active logging for plutonium (Kasper et al., 1980). The neutron detector in the moisture meter, however, was not as sensitive a logging system as the active system. Measurements were taken for 2-min counts at specific positions in the well as opposed to a continuous log. The volume of interrogation for passive logging is similar to that for copper foils, approximately 4,000 L. The results are reported in Appendix D in terms of the neutron flux for a 2-min count. Appendix F compares the results of active and passive neutron logging and laboratory data in determining the distribution of plutonium and americium.

Active Neutron Logging. A prototype uranium logging system (Baker et al., 1978) being developed by Los Alamos National Scientific Laboratory (Los Alamos) was used to log Well 181. The results of the logging in both the 216-Z-1A and the 216-Z-12 Cribs, along with a description of the design and operation of the system, are in preparation as a Los Alamos report. The operation of the system and the results of logging Well 181 will be covered briefly here.

The downwell probe consists of a ^{124}Sb source that emits high-energy gamma rays, which produce low-energy neutrons (26- and 360-keV photoneutrons) by the (γ,n) reaction in a beryllium target. The neutrons diffuse into the surrounding sediment, inducing the fissioning of odd-mass plutonium isotopes (primarily ^{239}Pu). When a plutonium nucleus fissions, two or three neutrons with an average energy of 2 MeV are emitted promptly. These neutrons are detected in the probe with an 18-atm ^{4}He recoil proportional counter biased to prevent counting of the lower energy source and background neutrons. The volume of interrogation of the Los Alamos system is estimated as approximately 60 L, significantly smaller than that of the passive techniques. Results of the logging of Well 181 are reported in Table 12. A proper plutonium calibration facility for neutron-based logging systems is currently unavailable

TABLE 12. Active Neutron Logging Results for Well 299-W18-181.*

Depth (m)	Counts/sec	Depth (m)	Counts/sec	Depth (m)	Counts/sec	Depth (m)	Counts/sec
15.54	1.57	11.91	1.78	8.13	2.39	4.26	2.32
15.47	1.78	11.85	1.84	8.07	3.28	4.20	1.02
15.44	2.12	11.73	1.84	7.95	2.39	4.11	1.64
15.38	1.78	11.66	1.71	7.85	2.73	4.04	1.98
15.32	1.71	11.57	1.98	7.76	2.05	3.95	2.05
15.23	1.50	11.51	2.39	7.64	3.07	3.89	1.64
15.14	1.78	11.42	1.98	7.55	3.35	3.83	1.43
15.08	2.12	11.36	1.78	7.46	3.01	3.77	1.71
14.99	1.78	11.27	2.39	7.37	2.66	3.68	1.02
14.90	1.91	11.18	1.98	7.28	2.25	3.62	1.64
14.80	2.12	11.12	2.19	7.15	1.84	3.53	2.05
14.71	1.64	10.99	1.23	7.09	2.60	3.47	1.71
14.62	1.78	10.93	2.12	7.00	2.80	3.37	1.71
14.54	1.64	10.81	1.64	6.88	5.12	3.34	1.91
14.47	1.30	10.75	2.19	6.79	11.14	3.25	1.71
14.38	1.50	10.66	1.98	6.70	16.60	3.19	1.23
14.29	1.98	10.57	2.25	6.57	25.82	3.10	1.37
14.19	1.57	10.51	1.64	6.48	36.55	3.04	2.05
14.10	2.32	10.42	1.91	6.42	44.82	2.95	1.23
14.01	1.64	10.35	1.98	6.36	50.90	2.89	1.78
13.95	1.50	10.23	1.43	6.27	56.50	2.83	1.30
13.86	2.32	10.17	2.12	6.21	53.63	2.73	1.37
13.77	1.84	10.08	1.98	6.12	44.68	2.64	1.84
13.71	1.57	9.99	2.66	6.03	33.41	2.55	1.64
13.62	1.91	9.90	2.60	5.93	21.66	2.43	1.57
13.52	1.91	9.81	2.73	5.84	12.30	2.37	1.16
13.43	2.12	9.74	3.55	5.75	7.51	2.28	1.30
13.37	2.12	9.62	3.69	5.66	4.30	2.22	1.43
13.25	2.19	9.53	2.80	5.57	3.69	2.12	1.64
13.19	2.32	9.44	3.14	5.48	2.60	2.06	1.37
13.10	2.60	9.35	2.87	5.39	2.19	1.97	1.57
13.01	2.53	9.29	2.46	5.32	1.84	1.91	1.64
12.91	2.87	9.17	2.12	5.20	1.98	1.82	1.43
12.82	1.98	9.10	2.60	5.14	1.43	1.73	1.23
12.73	2.19	8.98	2.25	5.02	1.30	1.64	1.16
12.64	1.78	8.92	2.39	4.93	2.66	1.55	1.50
12.58	1.57	8.83	1.98	4.87	1.57	1.45	1.50
12.49	2.25	8.74	2.73	4.78	1.98	1.36	1.37
12.40	1.50	8.65	2.12	4.72	1.71	1.27	1.16
12.34	1.84	8.56	2.39	4.62	1.84	1.21	1.37
12.24	1.71	8.46	1.50	4.56	1.71	1.12	1.30
12.15	2.05	8.37	1.91	4.50	1.84	1.03	1.30
12.06	2.12	8.31	1.50	4.41	1.30	-	-
12.00	2.05	8.22	1.78	4.35	2.05	-	-

*Fifteen seconds per interval.

and the results are left in terms of counts per second. Appendix F compares the results from active neutron with passive neutron logging and laboratory data.

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RESULTS

The analytical data (sediment size distribution, moisture content, and transuranic activity) used to interpret the geology and the distribution of plutonium and americium beneath the 216-Z-12 Crib are presented in a series of figures (logs) for the individual wells. The log format provides a convenient summary of the data and permits comparison of the data within and among wells. The logs for Wells 152, 153, 157, 162, and 179 through 185 are shown in Figures 28 through 38.

In the log for each well, the results of granulometric analysis are given under "sieve data" using the notation previously described. The semiquantitative sediment descriptions recorded during drilling are listed under the "drill log." Drill log information is available for 0.3- to 0.5-m increments in each well; this provides the most complete coverage of the sediment type. The drill log information identifies the location of interfaces between sedimentary units and indicates the presence of cobble-sized particles that could not be collected in the sample storage containers (particle diameter greater than 7 cm). Sediment samples were collected every 1.5 m or at lithology changes, and not every sample available was sieved. The sieve data however, provided the quantitative description of the sediment texture used to identify individual units. The information from the sieve data and the drill log was used to construct a lithologic log showing an interpretation of the distribution of sediment types. Patterns representing sediment types, shown on page 87, were used to construct the log. The patterns indicated sediment units on the basis of major textural differences. The density of the individual patterns indicated the relative abundance of the various sediment-size classes as determined by the sieve data. Thus the pattern  represented a silty, sandy gravel or cobble unit. Textural variations considered minor, or lenses of limited extent in a major unit, were indicated by different densities of the patterns or overlaying of patterns. Units considered major on the basis of textural differences were separated by a solid line on the lithologic log.

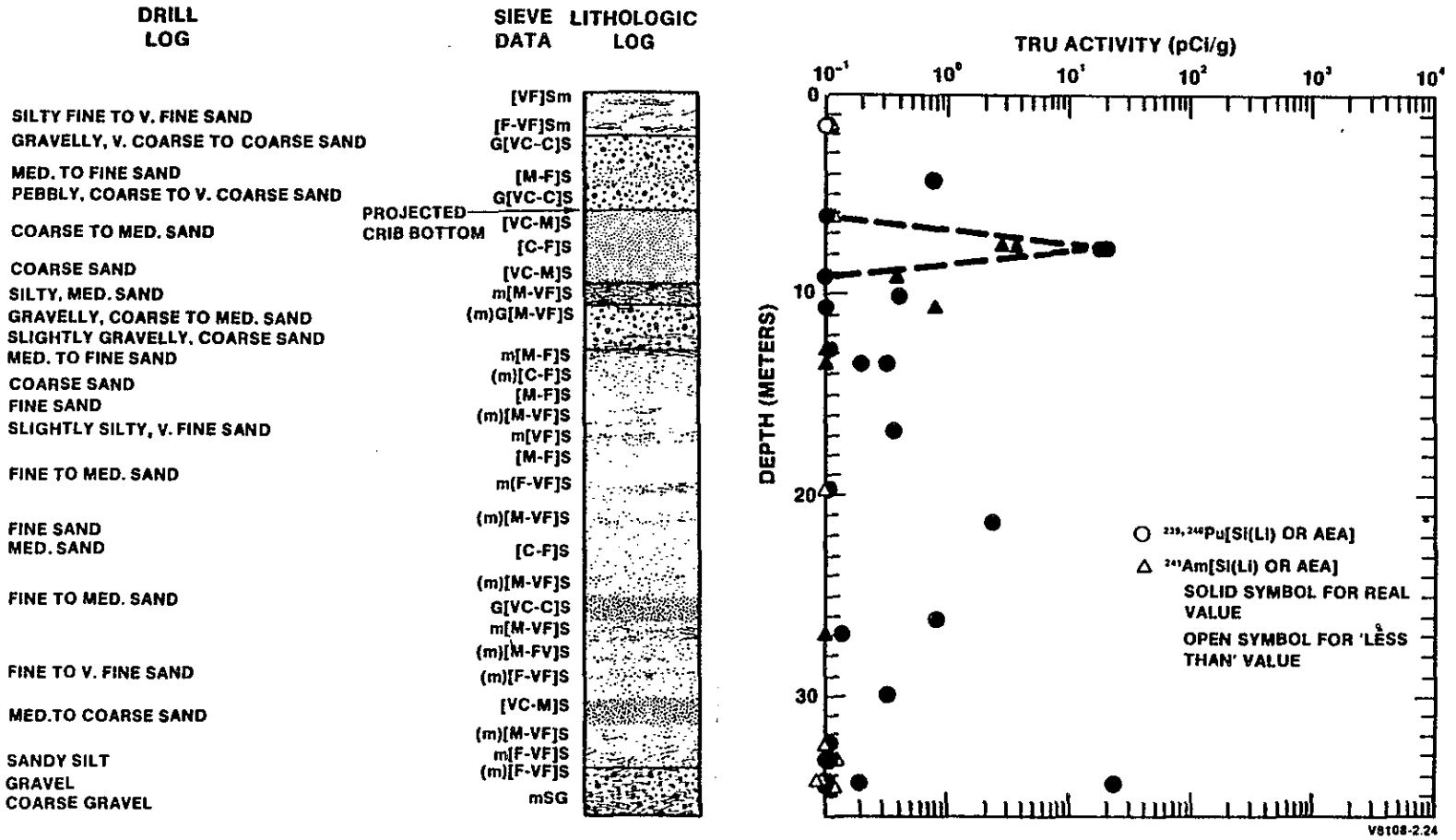


FIGURE 28. Log for Well 299-W18-152.

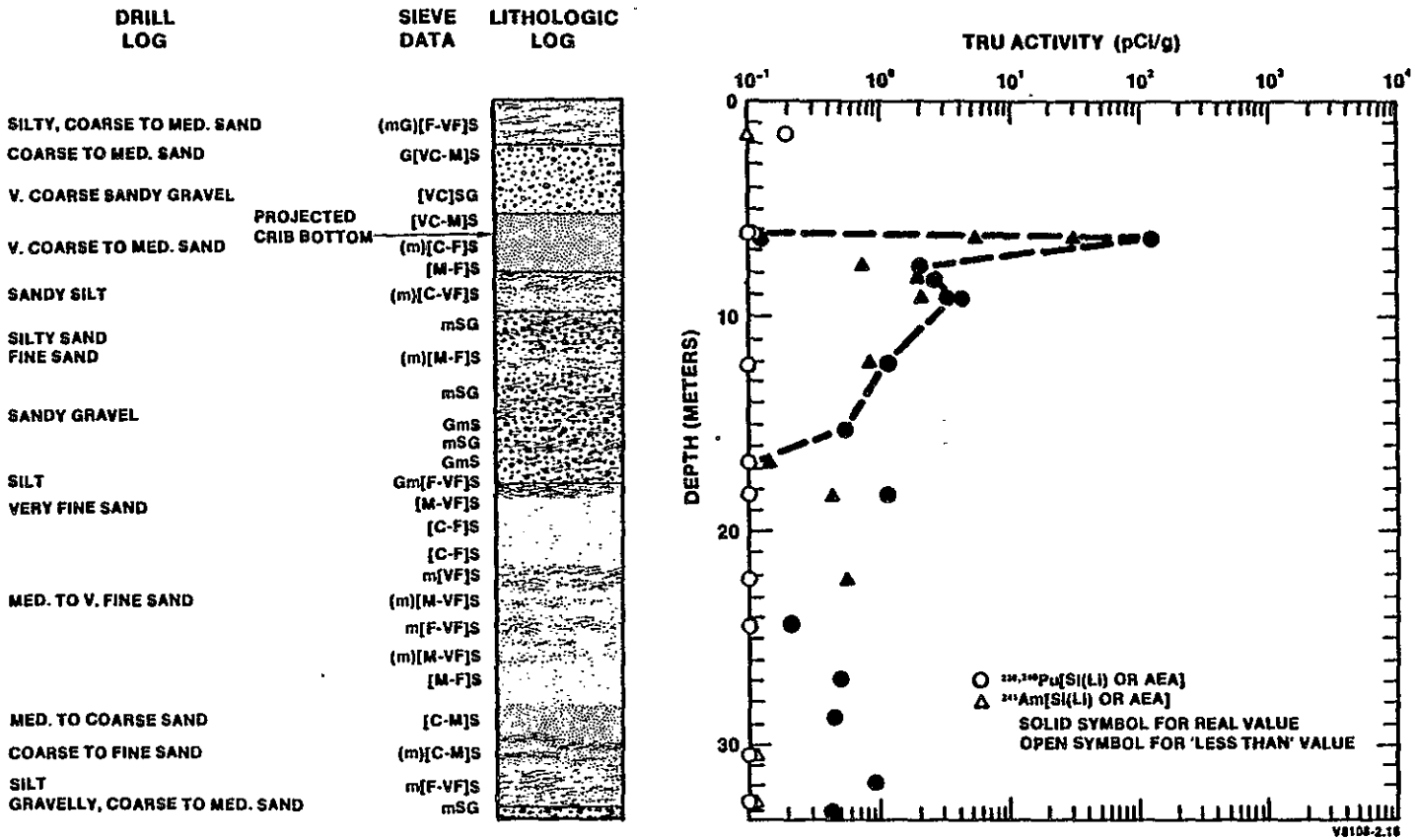


FIGURE 29. Log for Well 299-W18-153.

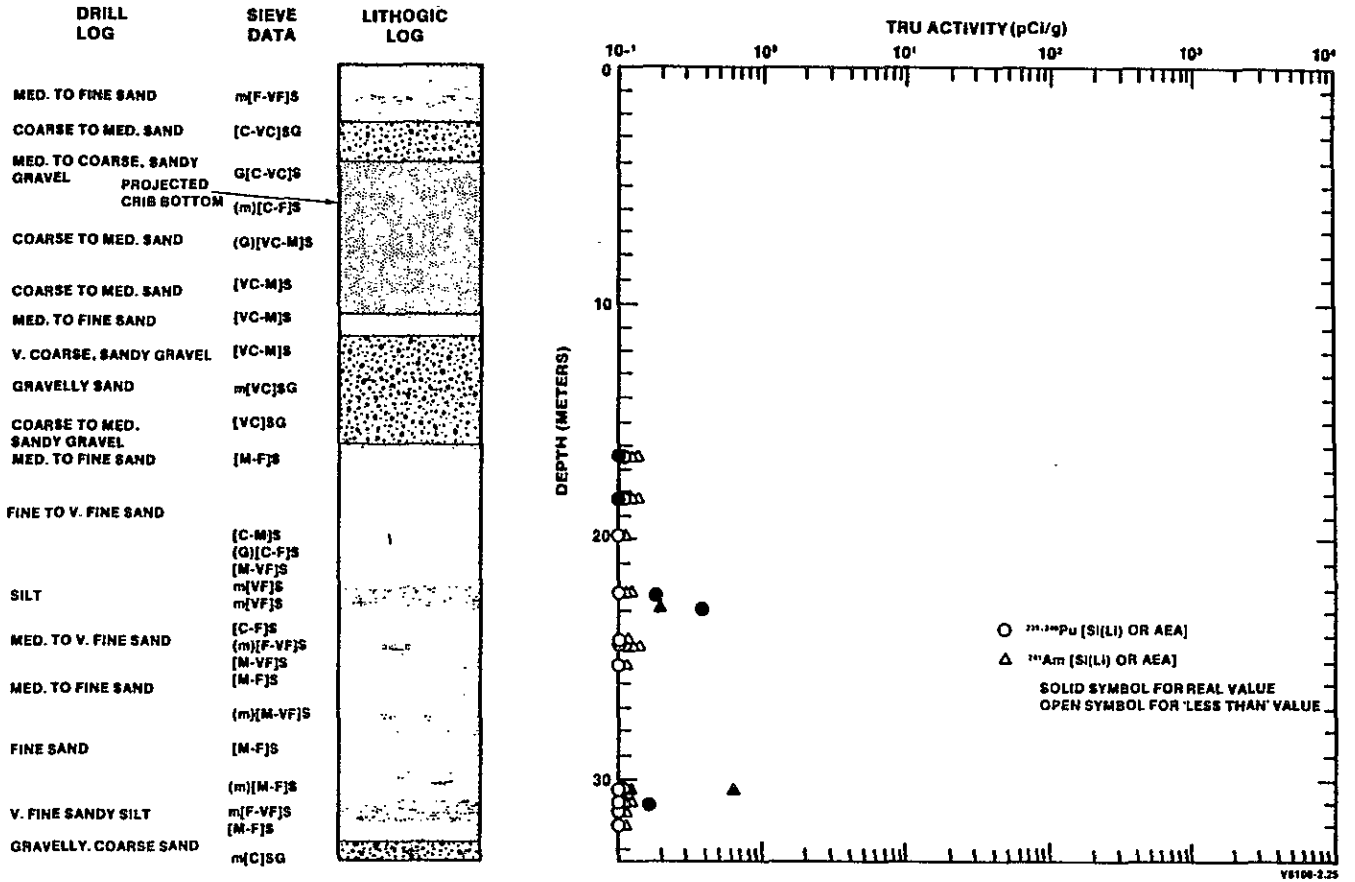


FIGURE 30. Log for Well 299-W18-157.

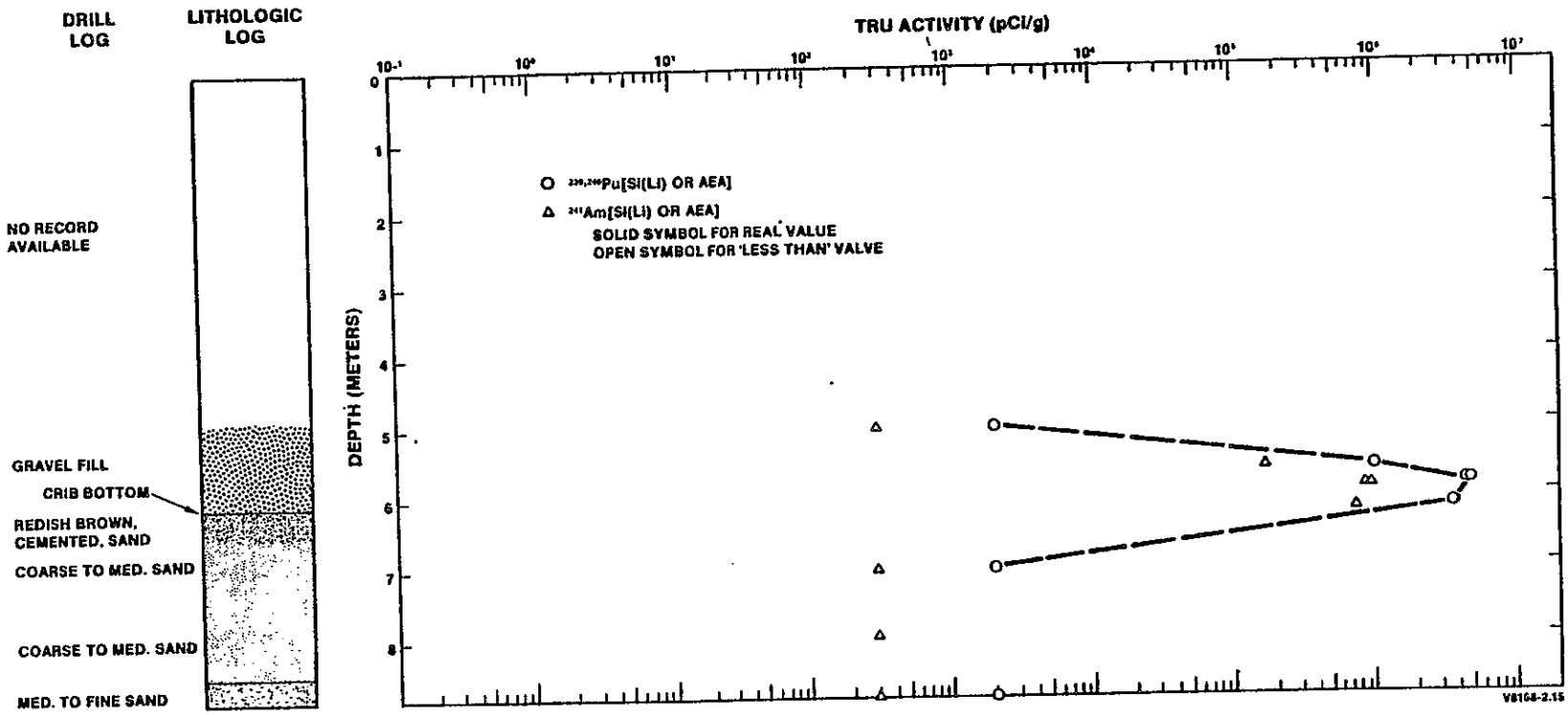


FIGURE 31. Log for Well 299-W18-162.

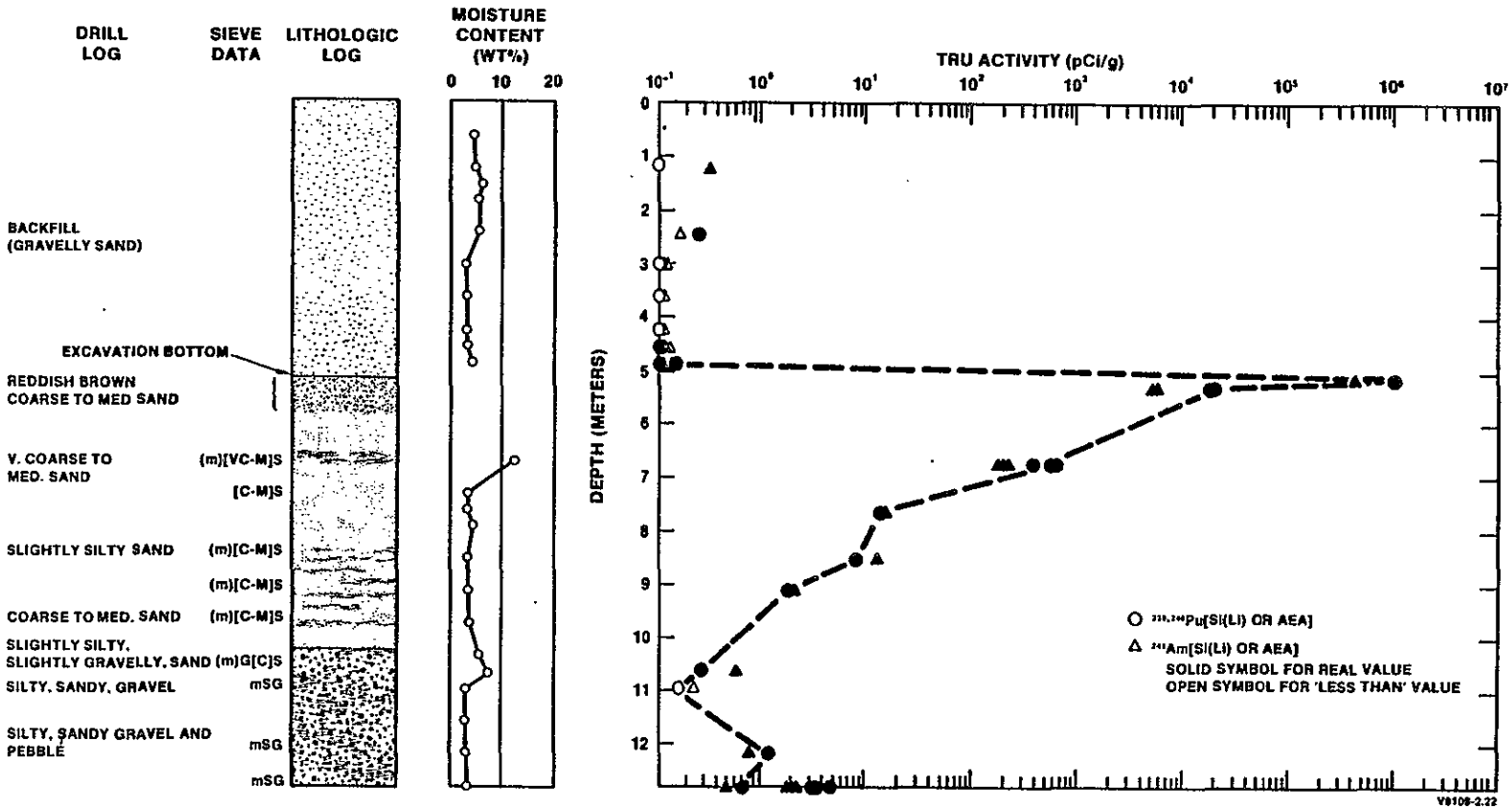


FIGURE 32. Log for Well 299-W18-179.

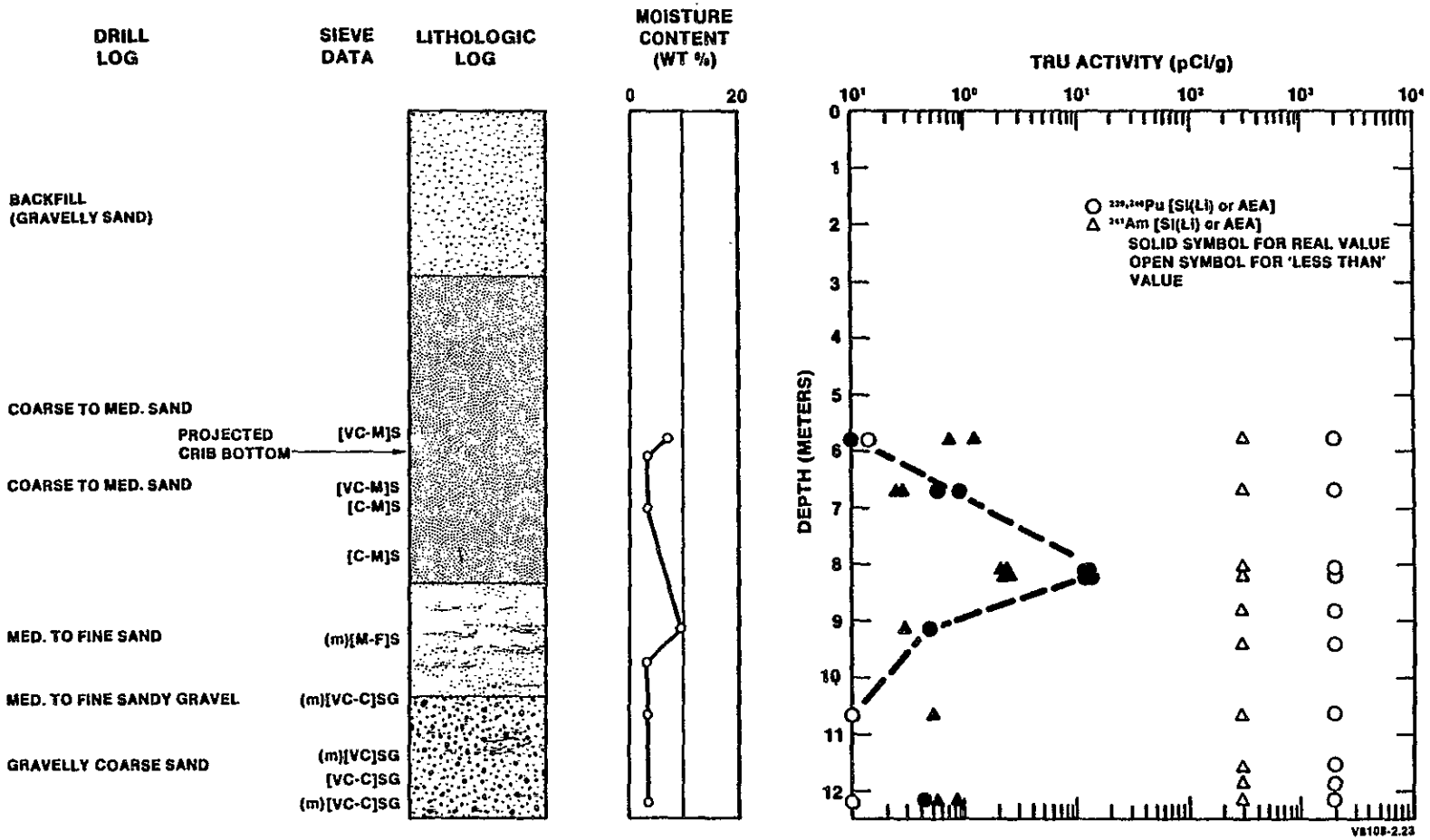


FIGURE 33. Log for Well 299-W18-180.

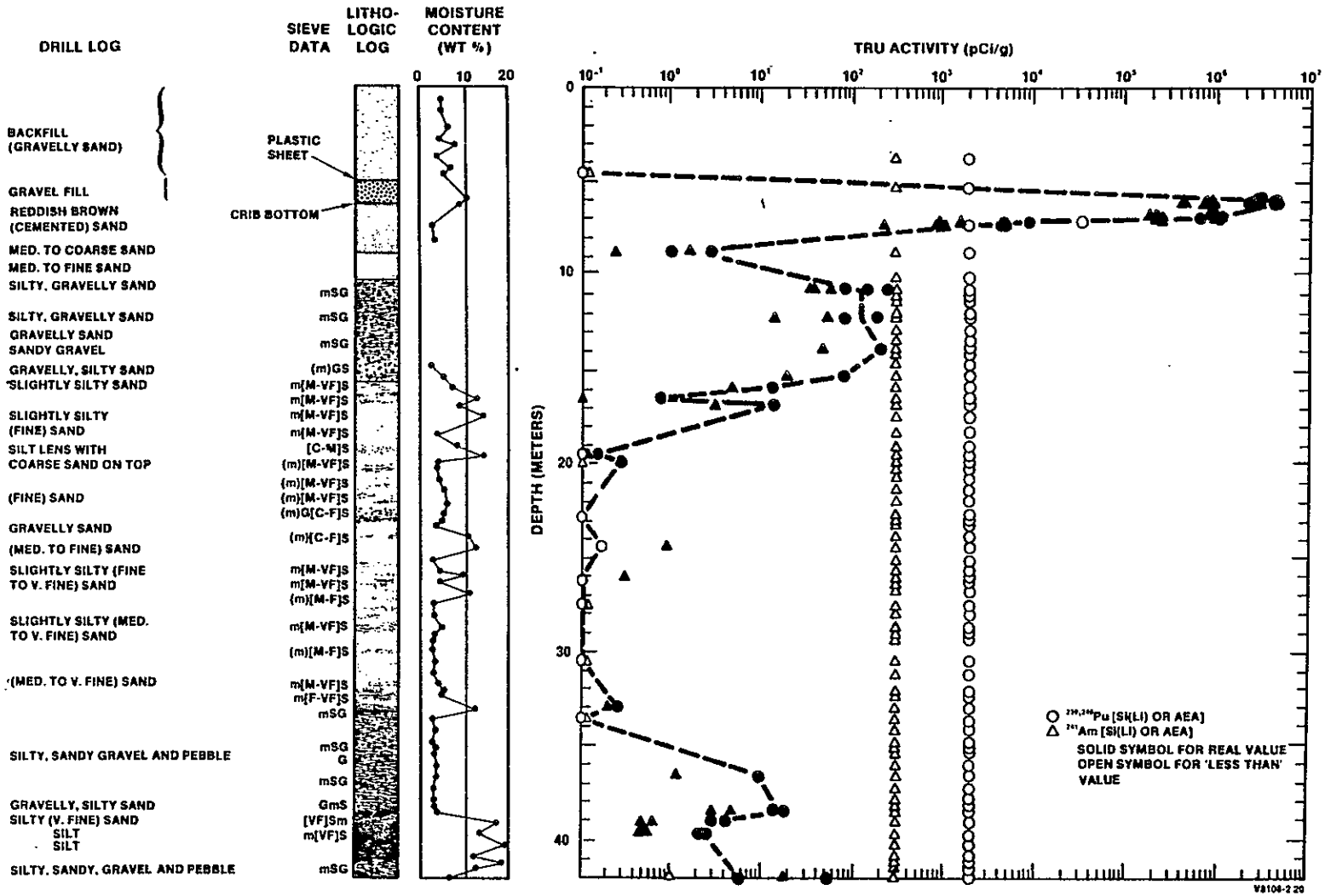


FIGURE 34. Log for Well 299-W18-181.

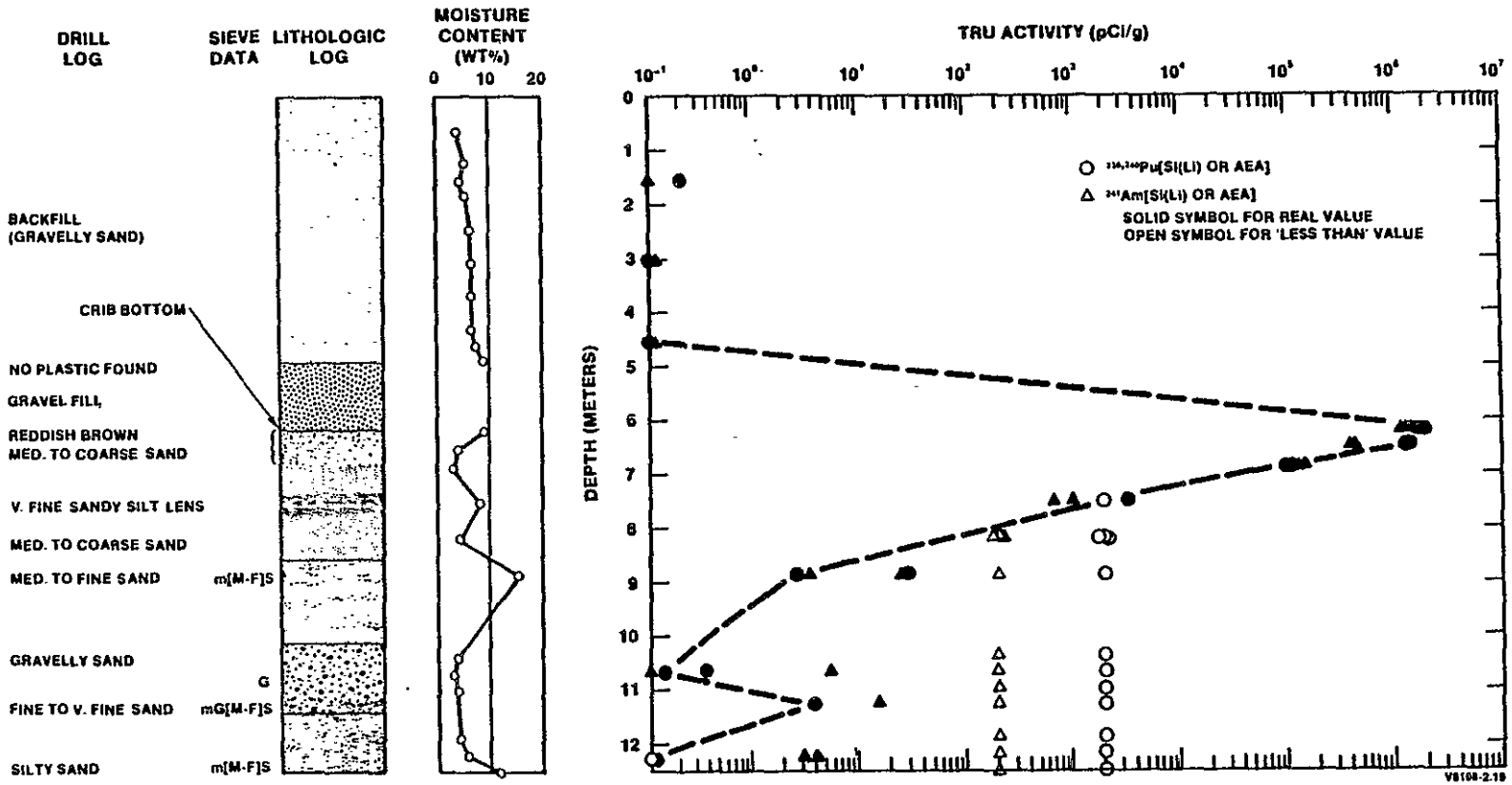


FIGURE 35. Log for Well 299-W18-182.

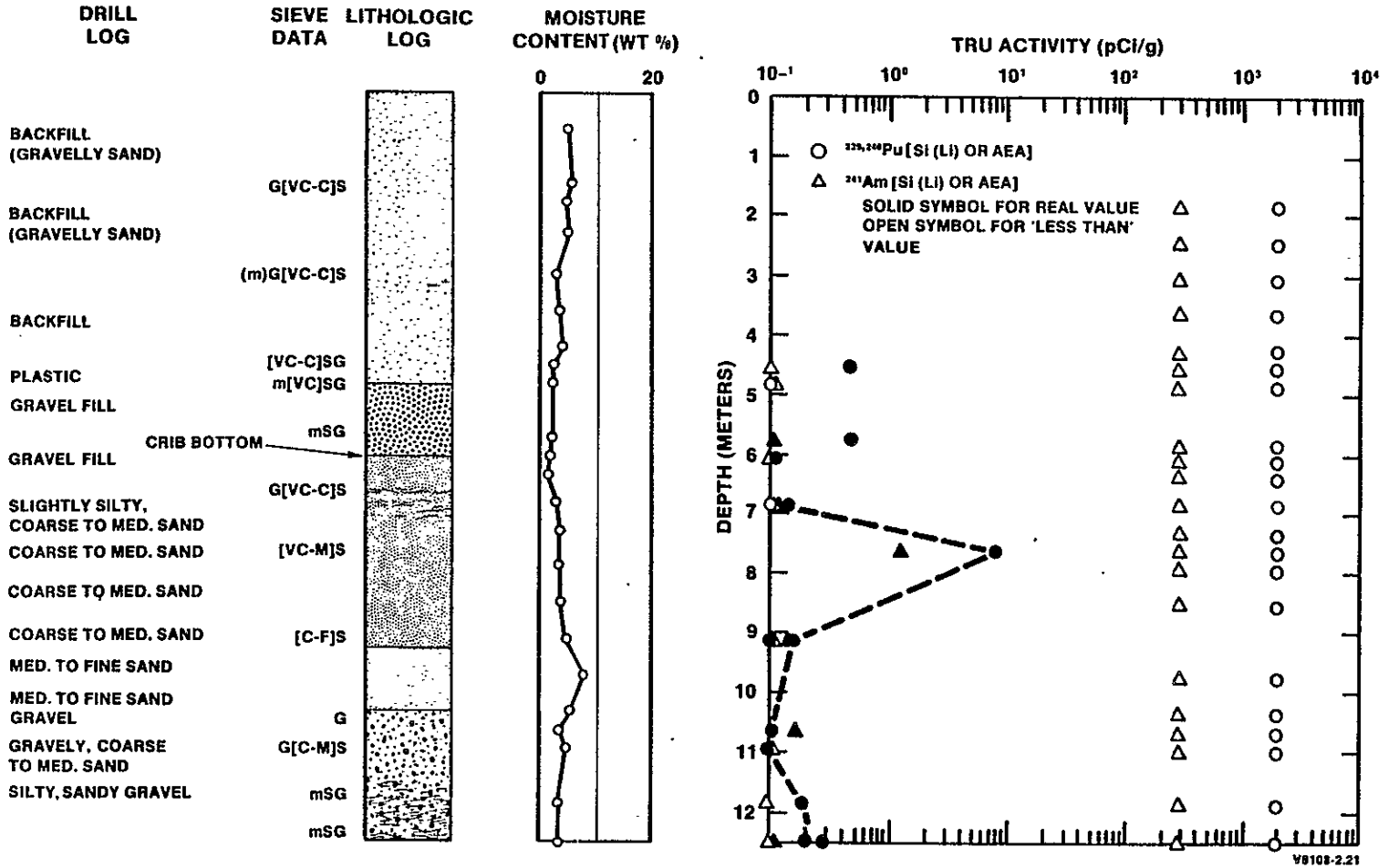


FIGURE 36. Log for Well 299-W18-183.

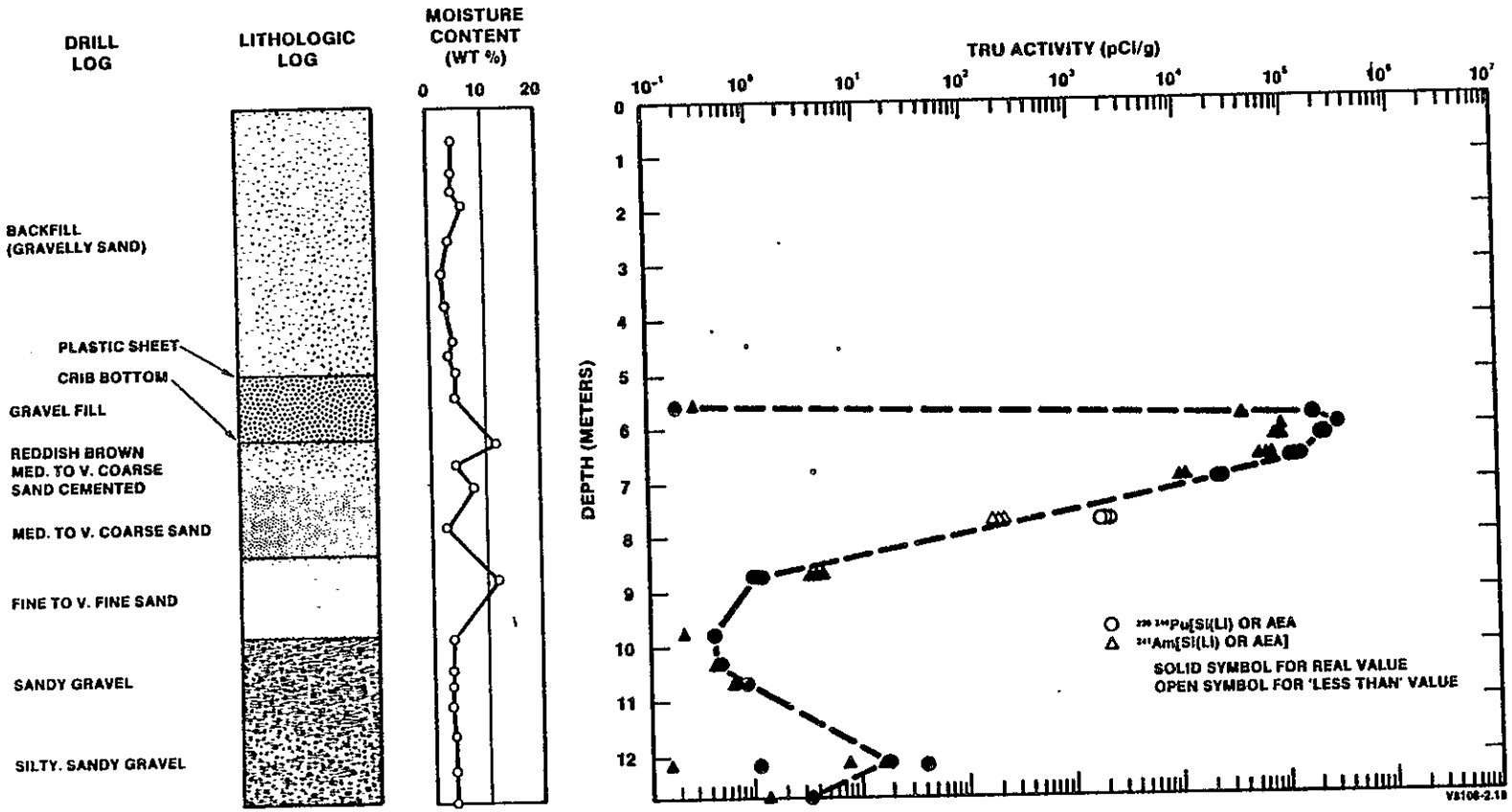


FIGURE 37. Log for Well 299-W18-184.

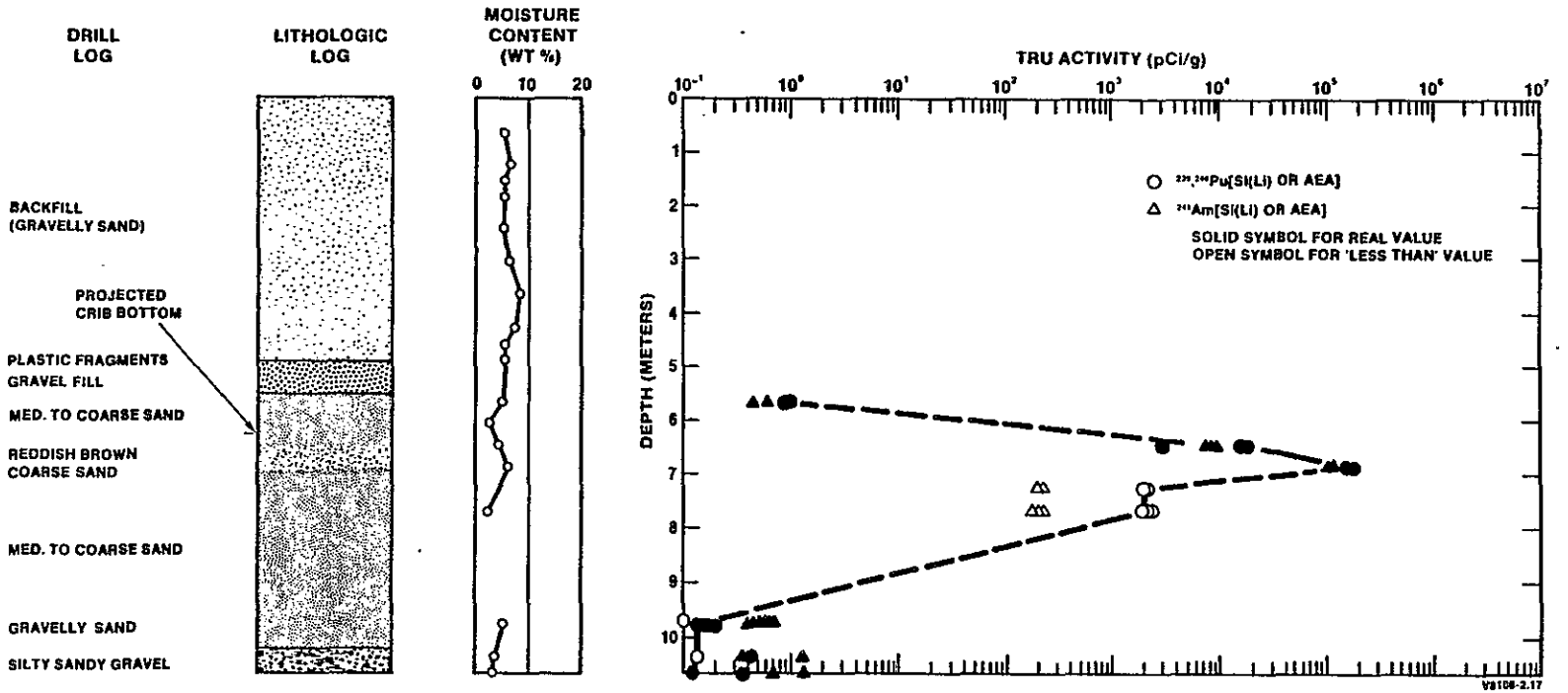
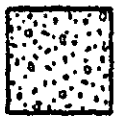
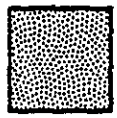
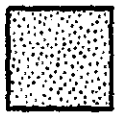


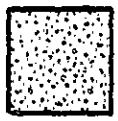
FIGURE 38. Log for Well 299-W18-185.

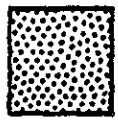

gravel and/or cobble


coarse sand


fine sand


silt


backfill


gravel fill

The results of gravimetric analysis for moisture content were reported in Appendix E. Moisture content in weight percent was plotted for comparison with the lithologic log.

The analytical data for plutonium and americium activity are reported in Appendix C. Activity profiles for $^{239,240}Pu$ and ^{241}Am were plotted in picocuries per gram for comparison with the lithologic log and moisture data. The data were differentiated as to "real" and "less than" values as identified in Appendix C. A dashed line connected data at each depth, indicating the trend in distribution, and aided in the visualization of the distribution. The line did not interpret the actual distribution with depth or between data points. The line generally passed through the average value where duplicate analyses were reported with the exceptions discussed below.

One of the exceptions was an analysis for a sample that was sieved to remove coarse material (>2 mm in diameter) and for which the activity was not in agreement with the other data. The finer material had a larger surface area per unit weight, which favored sorption reactions. In the 216-Z-1A Crib, higher activity of plutonium and americium was generally associated with the finer size fractions (Smith and Additon, 1980). Sieving the material to remove the coarse material could have biased the results; spuriously high results for sieved samples were ignored. Another exception occurred when an analysis reported from the

1976 study of Wells 152 or 153 indicated activity, while aliquots taken for the current study or surrounding samples did not. The trend in plutonium and americium distribution defined by the samples taken as part of the current study and subject to quality control checks used by the current study were considered more reliable.

The laboratory data presented in the logs were supplemented by neutron logging of the individual wells. The neutron flux measurements obtained by logging were useful as an aid in visualization of the transuranic distribution and were in general agreement with the laboratory data. Characteristics of the systems, however, made determination of the transuranic distribution dependent solely upon the laboratory analyses. Because of the limitations and the qualitative nature of the neutron flux measurements, neutron logging results are not covered in this section but discussed in detail separately in Appendix F.

Results from individual wells are discussed in groups according to their relation to the crib bottom. Wells 152, 153, and 157, which were drilled around the perimeter of the crib, and define the lateral extent of activity, comprise one group. Wells 75, 162, 181, 182, and 183, which penetrate the bottom of the crib, comprise a second group. Wells 180 and 184, which do not penetrate the bottom of the crib and are used with Wells 152 and 153 to define lateral distribution of plutonium, comprise a third group. Finally, Wells 154 and 179, which were drilled between the crib proper and the diversion box, comprise a fourth group.

Wells 152, 153, and 157 are located around the perimeter of the crib and were drilled during the 1976 study. Additional samples were selected from storage for granulometric analysis and laboratory analysis of transuranic activity. Both the analytical results from the 1976 work and the current study are plotted. Since the samples had been stored for an extended period of time, no samples were analyzed for moisture content. The logs for Wells 152, 153, and 157 are shown in Figures 28, 29, and 30, respectively. Results from Wells 152 and 153 indicate that plutonium activity peaked at a depth of approximately 7 m (23 ft) in both wells. In Well 152, peak activity was approximately

20 pCi/g, while in Well 153, peak activity was approximately 100 pCi/g. These results suggested lateral spreading of the waste liquid from the crib with plutonium and americium activity decreasing with distance from the crib. From the activity peaks, activity dropped below 1 pCi/g quickly with increasing depth. Several analytical results from the 1976 work indicated that activities exceeded 1 pCi/g deeper than 10 m in both wells. Duplicate analysis of aliquots of the same material collected from storage or nearby samples in the sediment column did not support levels of contamination greater than 1 pCi/g. Those older data were not considered in interpreting the distribution.

Well 157 is located at the southern end of the crib. Results from the wells drilled through the bottom of the crib indicated the waste never reached the southern third of the crib. As a consequence, lateral spreading of transuranic activity at the level of the crib bottom was not considered probable in Well 157, and emphasis was placed on analyzing sediment samples in the lower half of the well. The log for Well 157 indicated no activity greater than 1 pCi/g.

Wells 75, 162, 181, 182, 183, and 185 all penetrate the bottom of the crib. The data from Wells 162, 181, 182, and 183, in addition to Wells 179 and 157, were used to define the distribution of plutonium and americium down the length of the crib along cross section B-B' shown in Figure 20. Wells 75 and 162 were drilled in 1976. The analytical data for Well 75 were discussed previously (see Figure 17). The analytical data for Well 162 were obtained as part of the current study. Logs for Wells 162, 181, 182, 183, and 185 are shown in Figures 31, 34, 35, 36, and 38, respectively.

In Wells 162, 181, 182, and 185, the highest levels of plutonium and americium activity (1 to 6 million pCi/g) occurred immediately below the crib bottom at approximately 6 m (20 ft) below ground surface. Activity decreased rapidly with distance from the crib bottom. In all wells, activity was less than 1,000 pCi/g within approximately 2 m (6 ft) of the crib bottom. For Well 181, the deepest well drilled during the current study, plutonium activity was less than 1 pCi/g, 12 m below the crib bottom. The results for the wells drilled in the

current study did not agree with the results reported previously for Well 75; those data indicated greater than 1,000-pCi/g activity 3 to 4 m below the crib bottom. The drilling technique improvised for the well was not adapted to the situation and samples in the glove box may have been cross contaminated. Since the results for Well 75 did not agree with the wells drilled in the current study, the distribution of transuranic activity observed for Well 75 was not considered in this study, except for the five samples analyzed by AEA.

The sediments located immediately below the crib bottom, which had the highest concentration of plutonium and americium, were reddish-brown due to a coating that probably precipitated from the waste solution. In several wells, the coating had cemented the sediment grains together. The color was a useful marker of transuranic contamination of the sediment. Even a reddish-brown tinge to the sediment indicated alpha activity detectable using the portable radiation survey instruments.

Well 183 had a single sediment sample with plutonium activity greater than 1 pCi/g. Since the well is less than 1 m from the distribution pipe and penetrates the bottom of the crib, the result indicated that the waste liquid never was discharged to the southern third of the crib.

Parts of the plastic sheet placed in the crib to act as a moisture barrier were found in Well 184, which penetrated the gravel fill, and in all of the wells drilled through the crib bottom except Well 182. It is surmised that the plastic around Well 182 was removed during the excavation for the diversion pipe in 1968 and was never replaced. Activity in the backfill in Well 182 indicate no transuranic activity greater than 1 pCi/g. No alpha activity was detected by portable radiation survey instruments on any of the plastic.

The plutonium and americium distributions seemed similar in the wells, with americium activity approximately 20% to 25% of the level of plutonium activity. Americium-241 is produced by the beta decay of ^{241}Pu. For freshly processed plutonium, ^{241}Am activity gradually grows in, reaching a maximum 68 years after production. The ^{241}Am-to-^{239}Pu

ratio depends on the initial isotopic composition of the plutonium, and the elapsed time since it was purified. For the nominal composition of weapons grade plutonium (93 wt% ^{239}Pu, 6 wt% ^{240}Pu, and 0.6 wt% ^{241}Pu) reported by Emery and Garland (1974), the maximum value the ratio can attain is 0.16; the ratio reaches a value of 0.1 approximately 20 years after purification. The actual isotopic composition of weapons grade plutonium was variable, and some power reactor plutonium also may have been discharged to the 216-Z-12 Crib. Thus, the observed ratio was not considered significantly different than the ratio anticipated, and americium in the crib is considered to have decayed from ^{241}Pu in situ.

The moisture content did not appear to correlate with transuranic activity in any wells. The sediments immediately below the crib bottom could contain up to 10 wt% water, but the high transuranic activity was not always associated with high moisture content, nor did high moisture content indicate transuranic activity. High moisture content did mark the extent of the silt unit in Well 181 at a depth of 39 m.

Well 181, the deepest well drilled during this study, was drilled to a final depth of 42 m, 36 m below the crib bottom. Although no transuranic activity greater than 1 pCi/g was measured from 12 to 30 m below the crib bottom, activity increased from 30 to 36 m beneath the crib bottom. Activity levels ranged from a few to a few tens of picocuries per gram for plutonium. The underlying coarse sedimentary unit was not penetrated sufficiently to confirm the observations positively, but the activity is believed to be associated primarily with a silt unit identified at 33 to 35 m below the crib bottom. Considering the objectives of the study, and because of the low level of activity encountered, it was decided that additional deepening of the well was not warranted.

Wells 180 and 184 are west of the center of the crib and do not penetrate the crib bottom. Well 180 is 7.3 m (24 ft) from the distribution pipe, and 4.3 m (14 ft) from the crib bottom; Well 184 is 4 m (13 ft) from the distribution pipe, and 1 m (3 ft) from the crib bottom. The data from these wells helped define the lateral distribution of plutonium and americium from the crib along cross section A-A' (see Figure 20). Logs for Well 180 and 184 are shown in Figures 33 and 37, respectively.

Plutonium activity in Well 184 peaked at approximately 100,000 pCi/g at a depth of 6.8 m (22 ft). The level of activity was comparable to that measured immediately beneath the crib, although the depth was slightly greater than that found in wells through the crib bottom. For Well 180, peak activity was approximately 10 pCi/g at a depth of 8 m (26 ft). The results again indicated the waste solution spread laterally from the crib, but most of the plutonium and americium was quickly sorbed onto the sediment and exhibited only limited mobility with this waste type.

Wells 154 and 179 are approximately midway between the bottom of the crib and the diversion box. The log for Well 179 is shown in Figure 32. For Well 154, approximately 1 m of undisturbed sediment was recovered when the well was deepened to 6 m. The rest of the sediment consisted of backfill placed in the well in 1976 after contact with the alpha activity. Since the results of the neutron logging indicated that the sediments were probably disturbed and cross contamination of the sample possible, a separate log for Well 154 was not prepared. See Figure F-1, Appendix F, for a plot of the analytical data.

Transuranic activity in Well 179 peaked approximately 5 m (17 ft) deep, which is believed to be the depth of the excavation connecting the crib and the diversion box in which the distributor pipe was laid. Peak neutron flux measurements for Well 154 also corresponded to a depth of approximately 5 m. The highest level of plutonium activity in Well 179 was 1 million pCi/g, comparable to levels observed in wells drilled through the crib bottom. Peak plutonium activity in Well 154 was approximately 100,000 pCi/g.

DISCUSSION

Discussion of the study results is centered around two cross sections, A-A' and B-B', the location of which are shown in Figure 20. The cross sections illustrate the interpretation of the geology, and distribution of plutonium in the sediments beneath the crib derived from the results for the individual wells.

GEOLOGY

The data summarized for each well in the lithologic log were used to construct two cross sections illustrating the geology beneath the crib to the water table. One cross section, A-A', is perpendicular to the distribution pipe; the other, B-B', is parallel to the distribution pipe (Figures 39 and 40). The general characteristics of the geologic formations identified were discussed earlier. The cross sections show the detail of the formations beneath the 216-Z-12 Crib. Additional detail of the sediments comprising the Hanford formation are shown.

Beneath the 216-Z-12 Crib, the Hanford formation can be divided into six units. The units are identified on the basis of textural differences and are not anticipated to have extensive lateral continuity, considering the dynamic depositional environment of the Hanford formation. The uppermost unit is predominantly a coarse sandy pebble, which overlies a predominantly coarse sand unit. The third unit is a medium to fine sand unit. The transition from the coarse sand to the medium to fine sand unit is sharp and readily apparent in the field. The fourth unit is a silty sandy gravel. The fifth unit is predominantly a fine sand, although both silt and coarse sand lenses are present. The fine sand overlies another predominantly coarse sandy pebble unit, which in turn overlies the early Palouse soil.

PLUTONIUM DISTRIBUTION

The distribution of plutonium was interpreted from the analytical data for the individual wells. The plutonium distribution is plotted on the geologic cross sections for comparison in Figures 41, 42, and 43.

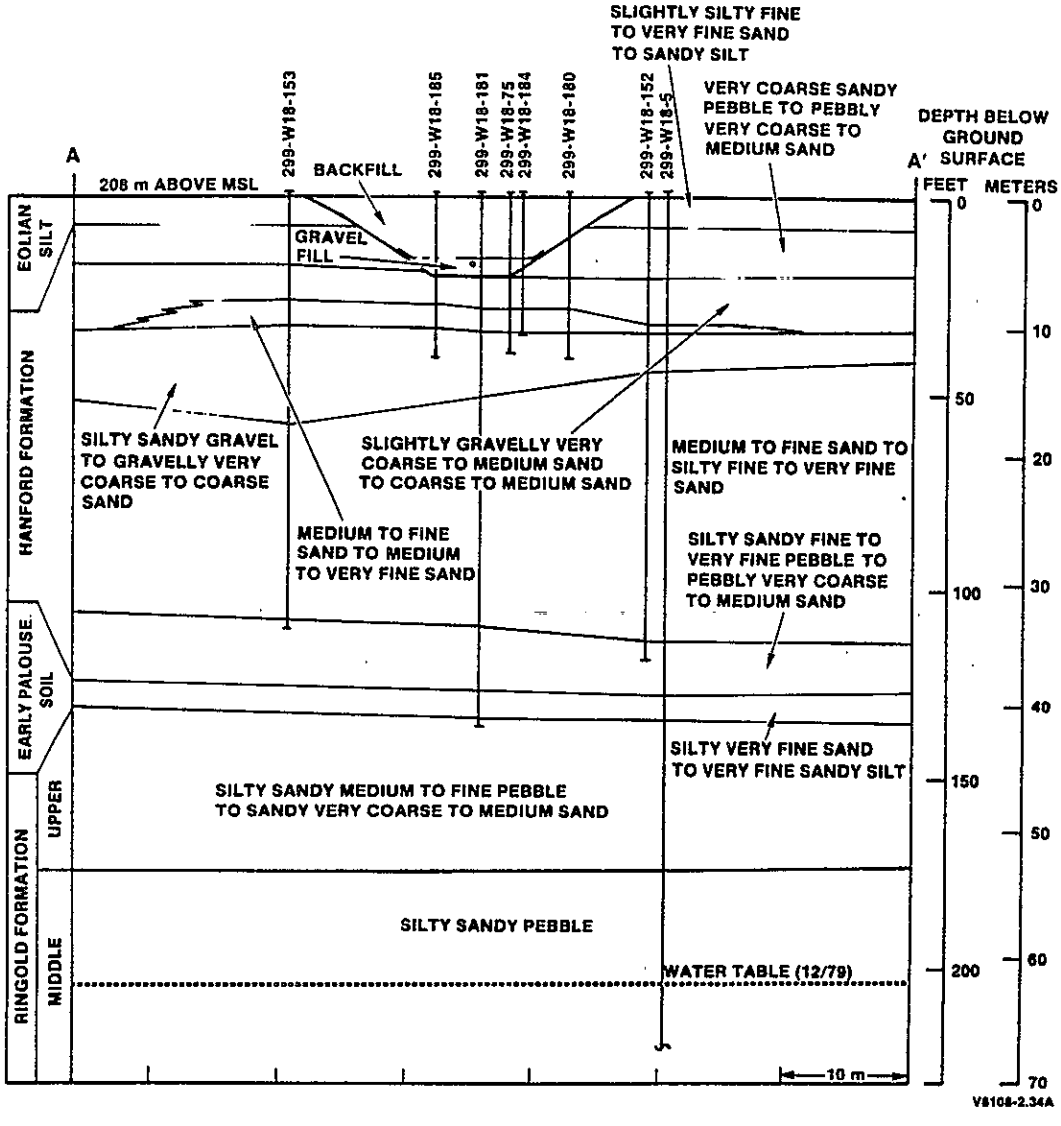


FIGURE 39. Geologic Cross Section A-A'.

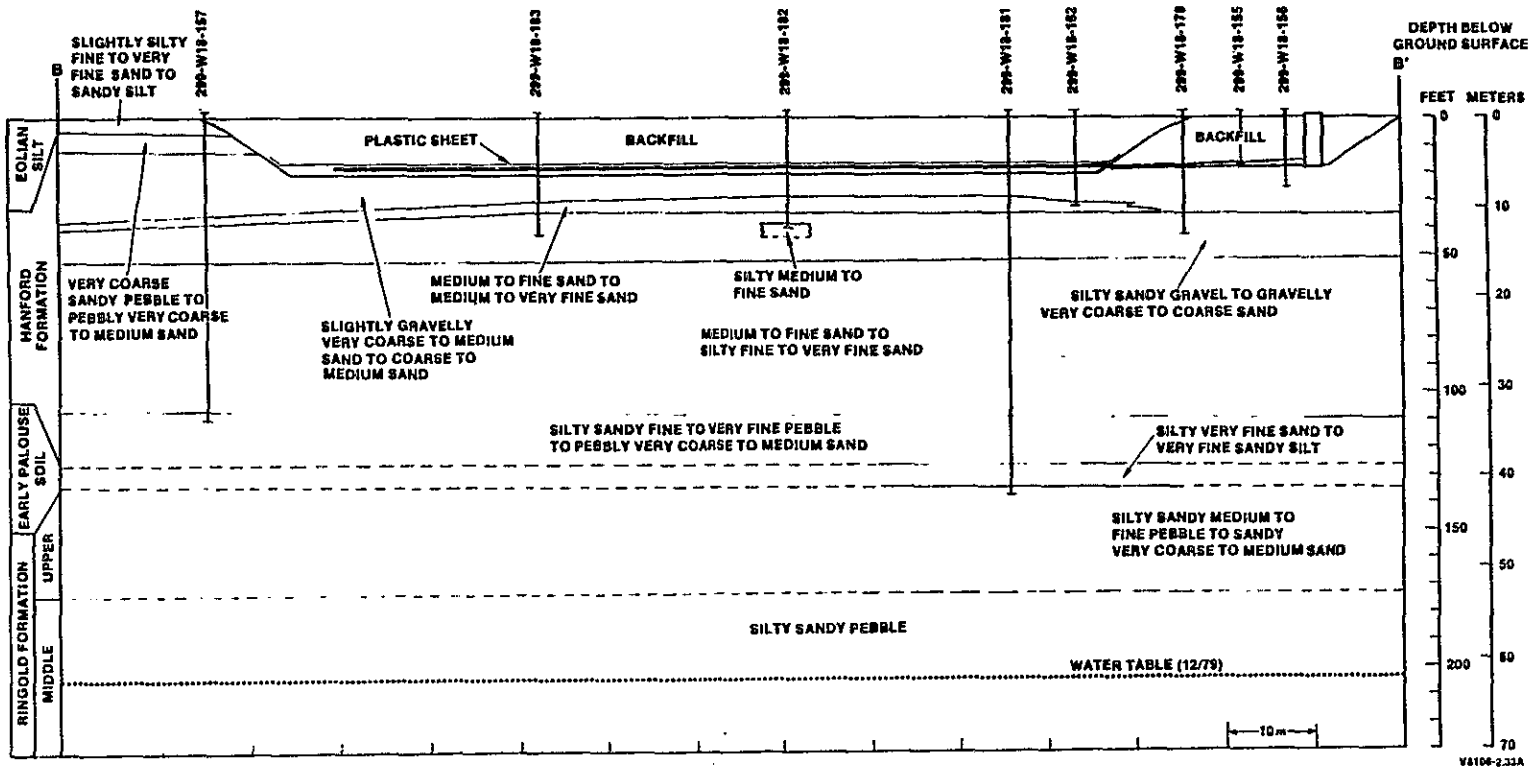


FIGURE 40. Geologic Cross Section B-B'.

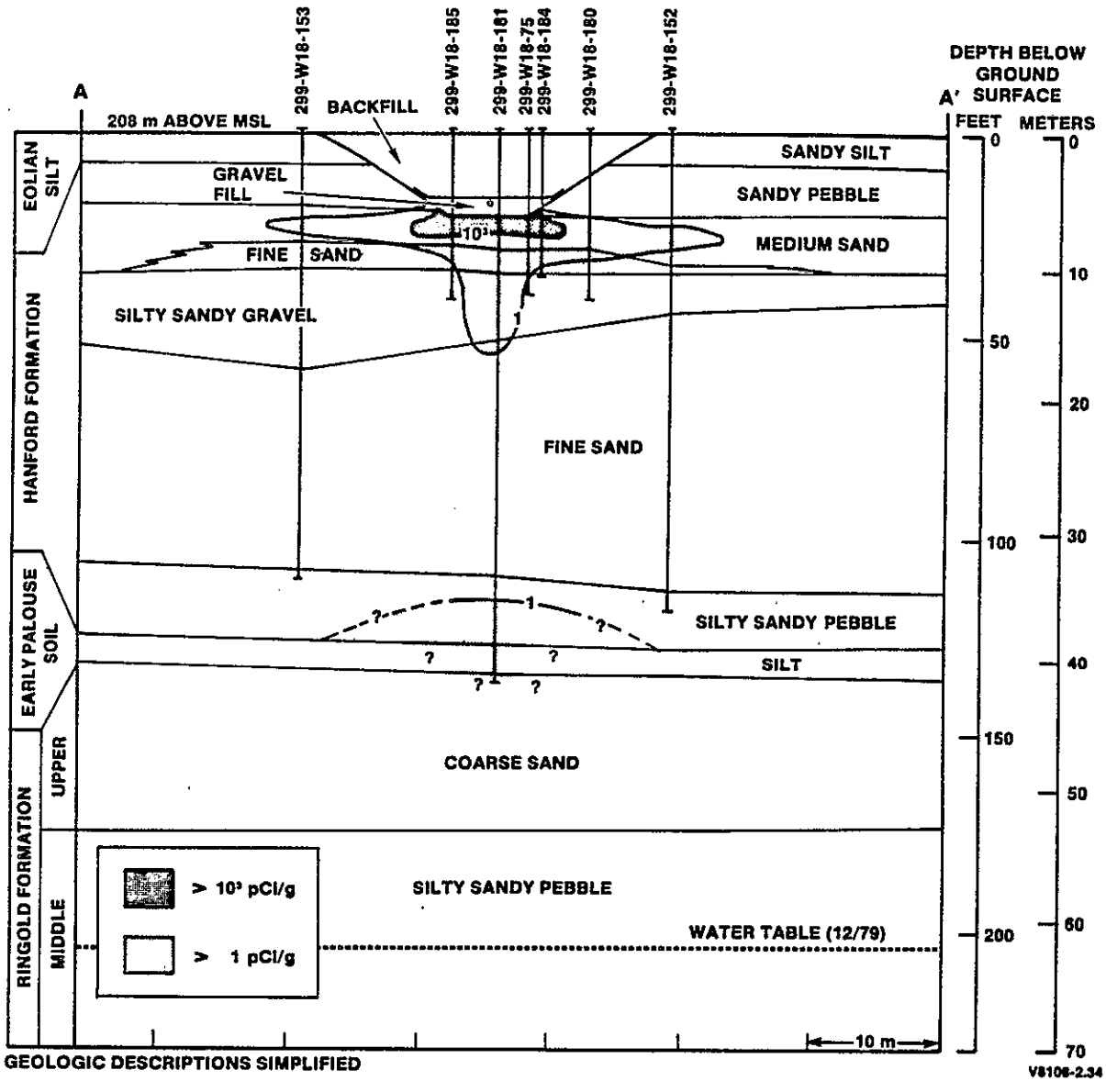


FIGURE 41. Plutonium Distribution of Cross Section A-A'.

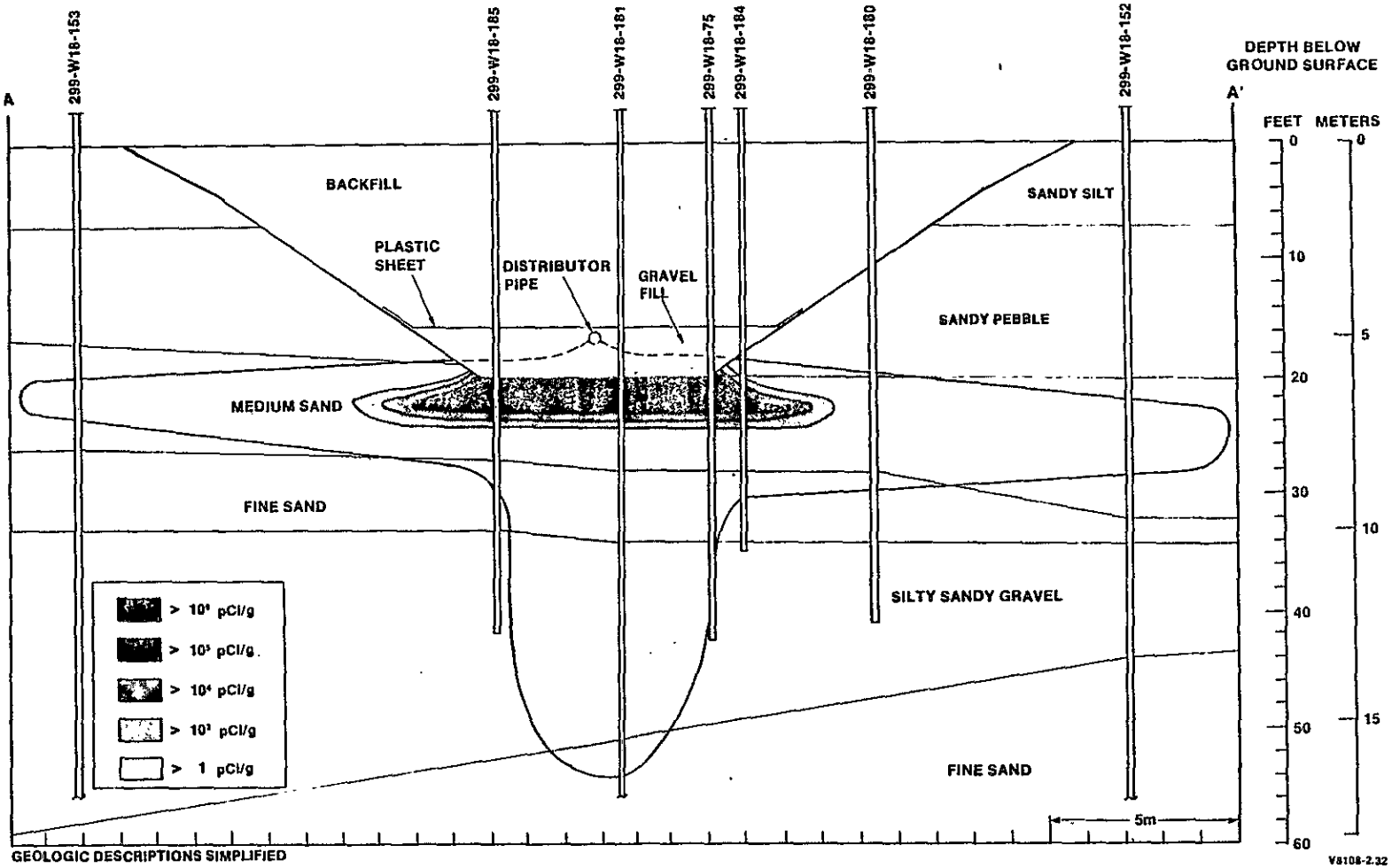


FIGURE 42. Plutonium Distribution of Cross Section A-A' Details.

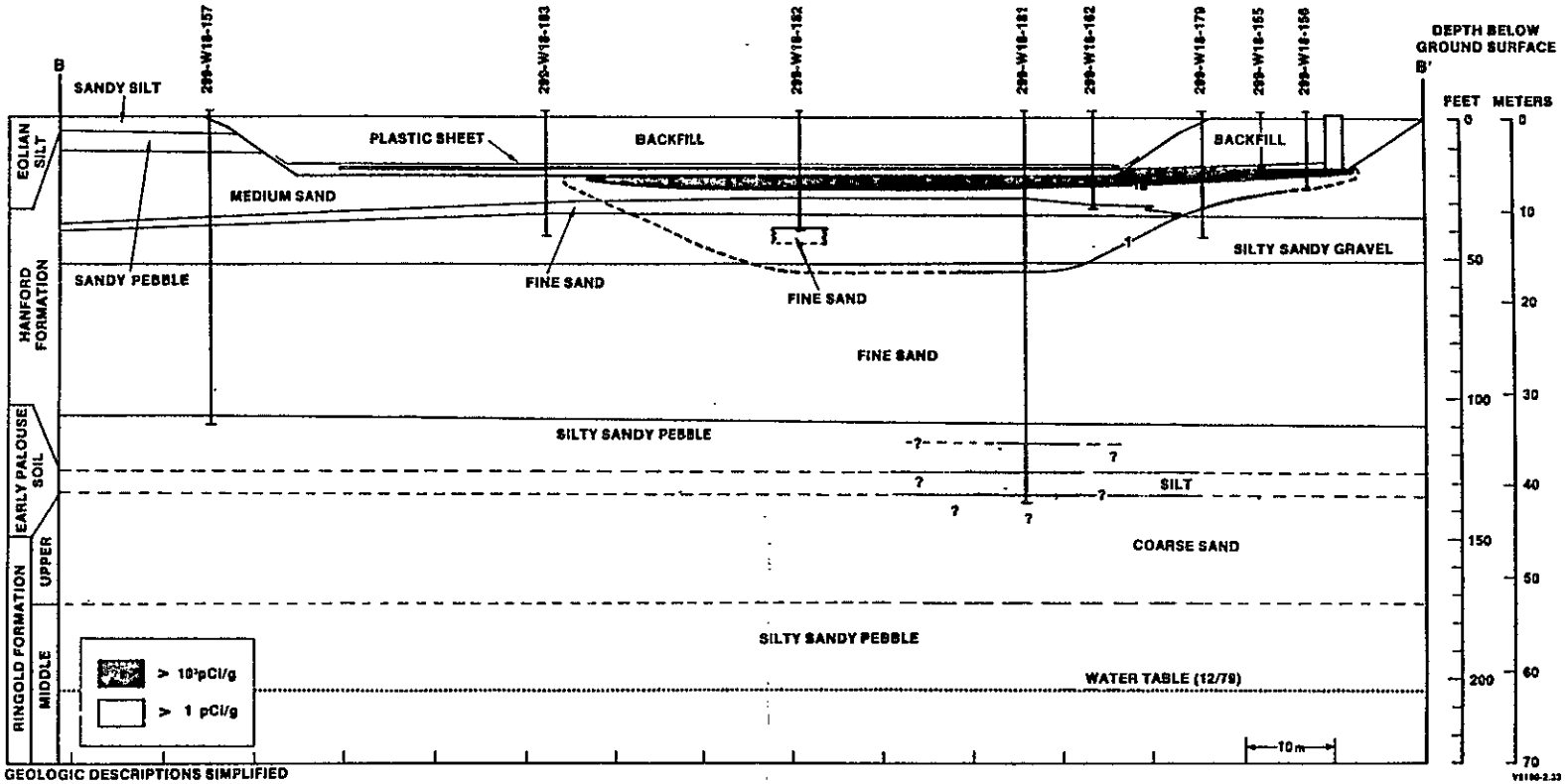


FIGURE 43. Plutonium Distribution of Cross Section B-B'.

Figure 41 shows cross section A-A'. The location of the individual wells are shown. Because of the scale, only the 1- and 1,000-pCi/g isopleths for plutonium were shown. While the major objective was to define the 10,000-pCi/g isopleth, the 1,000-pCi/g isopleth for plutonium was plotted in Figures 41 and 43 to provide a conservative estimate of the distribution. For the scale used in Figure 41, the difference between the 1,000 and the 10,000 isopleths was actually insignificant. Because of what appears to be a regular relationship between plutonium and americium activity, americium distribution and total transuranic activity were not plotted separately. Americium activity was assumed to be approximately 20% of the plutonium activity over most of the sediment volume. Figure 42 shows details of the contaminated volume immediately beneath the crib from Figure 41, and isopleths for plutonium activity of 1 million, 100,000, 10,000, 1,000 and 1 pCi/g. Figure 43 shows cross section B-B', illustrating the distribution of plutonium along the length of the crib. Again, because of the scale, only the 1- and 1,000-pCi/g isopleths for plutonium were shown.

The distribution of plutonium and americium is discussed in three parts corresponding to the objectives of the study outlined previously:

- To determine the general pattern of plutonium distribution at a level of 10,000 pCi/g or greater
- To evaluate the extent and level of plutonium activity between the crib and the diversion box
- To investigate the general pattern of transuranic activity with depth.

Distribution of Plutonium Activity Greater Than 10,000 pCi/g

The highest level of plutonium activity measured was 1 to 5 million pCi/g and was encountered in the sediments at and immediately below the crib bottom, according to neutron logging and visual observation of the core samples. This level was present in all wells that penetrated the bottom of the crib and encountered plutonium activity. Activity decreased rapidly with distance from the bottom of the crib, as is

illustrated clearly in Figure 42. Plutonium activity was less than 10,000 pCi/g within 2 m of the crib bottom. The highest plutonium activity for Well 180, approximately 4 m laterally from the crib bottom, was approximately 10 pCi/g. This activity level indicated limited lateral spreading of the plutonium in the waste. The bulk of the plutonium and americium in the waste was apparently removed from solution within the first 2 m of sediment below the crib bottom.

The distribution shown in Figure 42 is considered conservative for the estimated distribution at other points in the crib. Approximately 87% of the total volume of waste and 85% of the total plutonium inventory were discharged to the northern end of the crib before the 1968 diversion that bypassed the first 30 m (100 ft) of the distribution pipe.

Figure 43 shows the distribution of plutonium for cross section B-B'. The deeper penetration of plutonium beneath the crib in the northern end, as observed in Well 181, is believed to be due to the greater volume of waste discharged at that end. Results for Well 183, combined with the copper foil measurements in the gauge well and Well 72 (see Figure 21), indicated that the waste was not discharged to the southern end of the crib. The observation supported the 1967 study, which resulted in the 1968 bypassing of the northern third of the crib. The design of the distribution pipe failed to distribute the waste over the usable area of the crib bottom. Since the 216-Z-12 Crib design is typical of many cribs that received liquid radioactive waste, the same effect probably occurred at other sites; this was indeed the case in the 216-Z-1A Crib (Crawley, 1967).

Plutonium Activity Between the Crib and the Diversion Box

Plutonium activity was encountered in all four shallow wells (151, 154, 155, and 156) drilled during the 1976 study north of the crib. The activity was encountered in the wells at a depth of approximately 5 m (17 ft), which is considered to be the bottom of the excavation made to lay the distributor pipe. The source of the activity was previously thought to be a leak at the diversion box, which spread waste along the

interface between the excavated and unexcavated sediments. Results from wells drilled through the bottom of the crib, however, demonstrated that plutonium and americium were quickly sorbed on the sediment. Well 179 is approximately 10 m (32 ft) from the bottom of the crib and 14 m (45 ft) from the diversion box. Peak levels of transuranic activity encountered in Well 179 were comparable to those found in the crib; lateral spreading of plutonium in the waste from either the crib or the diversion box appeared impossible.

If the joints between the sections of unperforated VCT pipe used to connect the diversion box to the crib were indeed only butted together and not sealed as indicated by the engineering drawings, leaking of a significant volume of waste is possible. Leaking at the joints of the connecting pipe would easily account for the observed level of plutonium activity. It must be assumed that the plutonium contamination extends from the crib to the diversion box at the same level of activity observed in Wells 154 and 179.

Transuranic Activity Distribution with Depth

Transuranic activity decreases rapidly with distance from the crib bottom (see Figure 42). Plutonium activity is less than 1 pCi/g from 10 to 30 m below the crib bottom. Increased activity was observed in Well 181, from 30 to 36 m below the crib bottom; however, the levels of activity encountered were still low. In general, the level of activity was on the order of 20 pCi/g (the highest value was 60 pCi/g for a sieved sample). The source of this activity could be either the waste discharged to the 216-Z-12 Crib or from lateral spreading of waste solutions discharged to nearby liquid waste disposal facilities.

The two nearest liquid waste disposal facilities to the 216-Z-12 Crib are the 216-Z-1A and 216-Z-18 Cribs (see Figure 3). Both these cribs received "high-salt" waste. Laboratory studies (Knoll, 1965; Hajek and Knoll, 1966) indicated that for high-salt waste, plutonium sorption was minor and americium sorption negligible. A conclusion of the studies was that plutonium and americium would not be strongly sorbed near the bottom of the crib but would be carried with the waste solution, and

that all sediments contacted by the waste solution would be contaminated by transuranic elements. This conclusion was supported by a subsequent field study of the distribution of plutonium and americium in the 216-Z-1A Crib (Price et al., 1979; Kasper et al., 1979). Because of the mobility of plutonium and americium in high-salt waste, cribs receiving this waste type were classified as specific retention facilities. The volume of waste discharged to a specific retention facility is limited such that the aqueous phase will not reach the water table within a specified time period [30 years (Bierschenk, 1959)]. Because of the limited volume of waste discharged to the 216-Z-1A and 216-Z-18 Cribs, lateral spreading of waste from these facilities is not considered a source of the deep activity observed at the 216-Z-12 Crib.

The source of the deep activity in the 216-Z-12 Crib is thus considered to be the low-salt waste discharged to the crib. Activity decreases rapidly with distance below the crib bottom and detectable activity from 10 to 30 m below the crib bottom is less than 1 pCi/g. In addition, routine ground-water monitoring of the crib indicated that no measurable levels of transuranic activity were detected (see "Routine Ground-Water Monitoring" section). These observations indicate that most of the plutonium was effectively removed from the waste solution within the first 1 to 2 m of sediment below the crib bottom and that a concentrating mechanism resulted in the sorption of plutonium remaining in the waste at a depth of 30 to 36 m below the crib bottom.

Examination of the log for Well 181 indicate that the increased activity at depth is associated with the presence of the fine-grained silt unit identified as the early Palouse soil. A silt unit would have a higher sorption capacity than the surrounding coarser sand and gravel units because of the greater surface area per unit weight of silt-sized particles. Silt lenses were very effective in concentrating plutonium and americium from the waste solution in the 216-Z-1A Crib (Price et al., 1979); a similar effect was suspected in the 216-Z-12 Crib. In addition, caliche horizons, commonly associated with the silt unit and the top of the Ringold Formation, provided competing cations that would enhance the sorption of plutonium in solution. Furthermore, the massive silt unit

would impede the flow of the waste liquid. As a result, the waste liquid would be expected spread laterally along the top of the silt unit and would also have a longer residence time in the silt unit and the coarse unit above. The longer residence time could possibly result in additional exchange reactions, which in turn increase sorption of the remaining plutonium in the liquid waste.

The conclusion is that almost all of the plutonium was effectively removed from the waste solution by sorption reactions within the first few meters of sediment below the crib bottom. Low concentrations of plutonium remaining in the waste solution (at a concentration possibly less than 0.1 pCi/mL) were effectively removed by further sorption reactions with the silt unit. Breakthrough of measurable concentrations of plutonium to the ground water did not occur.

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CONCLUSIONS

The results of this study show that plutonium was effectively removed from the waste liquid discharged to the 216-Z-12 Crib by waste-sediment interactions. Almost all of the plutonium and americium activity occurs within a narrow zone beneath the crib. The bulk of the plutonium was sorbed onto the sediments within 3 m of the crib bottom. Levels of plutonium activity as high as 5 million pCi/g were measured immediately below the crib. Plutonium activity decreased rapidly with distance from the crib. Plutonium activity was less than 1,000 pCi/g, 3 m below the crib and less than 1 pCi/g, 12 m below the crib.

Levels of plutonium activity greater than 1,000 pCi/g were not confined solely to the volume of sediment immediately below the crib bottom. The VCT pipe connecting the diversion box to the crib leaked, resulting in contamination of the sediments from the diversion box to the crib. Plutonium activity levels encountered in this area were comparable to those beneath the crib bottom, and were present as a thin layer at a depth of approximately 5 m. In addition, the distribution pipe failed to spread the waste over the entire effective bottom area of the crib. The southern third of the crib did not receive waste.

No plutonium activity greater than 1 pCi/g was detected from 12 to 30 m below the crib bottom. However, a low level of plutonium and americium activity was detected from 30 to 36 m below the crib, the maximum depth sampled. Plutonium activity at this depth ranged from a few to a few tens of picocuries per gram. The observed distribution suggests that the increased activity is associated with the presence of a thick silt unit. The higher sorption capacity and low permeability of the silt unit offers the optimal situation for the sorption of plutonium in the waste. Routine ground-water monitoring of the 216-Z-12 Crib indicated the concentration of alpha-emitting radionuclides continued to be below the detection limit of 1.7×10^{-2} pCi/mL. The ground-water monitoring results, when considered with the effective removal of the bulk of the plutonium in the sediments immediately below the crib bottom and with the low level of activity found associated with the silt unit,

suggest that the increased activity is due to concentration of trace amounts of plutonium remaining in the waste by the silt unit. Measurable concentrations of plutonium did not break through to the ground water.

Plutonium and americium distribution were similar and the ratio of americium to plutonium activity beneath most of the crib was approximately 0.2. These results suggested that the americium activity observed beneath the 216-Z-12 Crib was derived primarily from the in situ decay of ^{241}Pu discharged in the waste.

The results of this study define the pattern of plutonium and americium distribution in the sediments underlying the 216-Z-12 Crib. The data base can be used as a guide for continued monitoring of the waste plume, for management decisions concerned with the future disposition of the site, and for comparison of the actual behavior of plutonium and americium in this environment with that predicted on the basis of laboratory experiments.

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APPENDICES

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APPENDIX A

WASTE DISPOSAL TO THE 216-Z-12 CRIB
MARCH 11, 1959 TO MAY 15, 1973

Period	Vol ($\times 10^6$L)	Plutonium (g)
January 1959	--	--
February	--	--
March	2.42	25.5
April	3.99	63.7
May	4.55	77.9
June	5.90	118.6
6-mo Total	(16.8)	(285.7)
July	5.34	37.05
August	5.10	65.56
September	3.44	94.22
October	2.94	179.68
November	2.88	146.28
December	4.26	467.13
6-mo Total	(23.96)	(989.9)
TOTAL FROM 3/59	40.76	1,276.0
January 1960	3.158	371.42
February	3.402	29.04
March	3.091	60.83
April	3.55	1,102.08
May	3.244	71.41
June	3.981	89.13
6-mo Total	(19.43)	(1,723.9)
July	3.174	387.29
August	4.645	59.6
September	4.206	110.9
October	3.113	41.6
November	4.086	95.7
December	4.484	88.7
6-mo Total	(23.7)	(783.79)
TOTAL FROM 3/59	83.90	3,783.7

Period	Vol ($\times 10^6$ L)	Plutonium (g)
January 1961	4.112	92.5
February	3.752	87.0
March	3.047	649.2
April	2.926	272.5
May	2.620	194.0
June	4.514	192.0
6-mo Total	(20.971)	(1,487.2)
July	2.566	443.0
August	3.449	238.0
September	3.778	121.0
October	3.578	86.0
November	2.698	851.0
December	3.678	366.0
6-mo Total	(19.7)	(2,105.0)
TOTAL FROM 3/59	124.6	7,395.9
January 1962	2.64	684.0
February	2.23	295.3
March	2.47	60.0
April	--	--
May	0.64	43.2
June	3.47	113
July	2.52	118.9
August	2.15	103
September	2.25	157
October	2.15	272
November	1.68	563
December	2.28	436
12-mo Total	(24.48)	(2,843.6)
TOTAL FROM 3/59	149.1	10,239

Period	Vol ($\times 10^6$ L)	Plutonium (g)
January 1963	2.71	528.60
February	2.33	336.00
March	2.11	383.00
April	2.29	226.00
May	1.26	266.42
June	1.61	235.00
July	1.51	286.00
August	1.35	551.00
September	1.70	254.00
October	2.07	224.00
November	1.68	291.00
December	1.62	261.00
12-mo Total	(22.24)	(3,842)
TOTAL FROM 3/59	171.3	14,081
January 1964	1.97	242
February	1.16	229
March	1.43	334
April	1.24	334
May	1.36	411
June	1.62	154
July	1.43	248
August	1.53	126
September	1.38	257
October	1.58	212
November	2.07	349
December	1.69	303
12-mo Total	(18.5)	(3,199)
TOTAL FROM 3/59	190	17,280

Period	Vol ($\times 10^6$ L)	Plutonium (g)
January 1965	1.727	279
February	1.252	430
March	2.228	232
April	1.773	222
May	1.651	111
June	1.625	103
July	1.289	118
August	1.113	120
September	1.663	28
October	0.871	38
November	1.000	86
December	0.631	97
12-mo Total	(16.82)	(1,864)
TOTAL FROM 3/59	207	19,144
January 1966	1.16	53
February	1.28	143
March	1.50	98
April	1.21	121
May	1.11	38
June	0.86	13
July	0.68	97
August	0.77	24
September	1.22	23
October	1.48	26
November	1.43	58
December	2.05	73
12-mo Total	(14.75)	(767)
TOTAL FROM 3/59	222	19,911

Period	Vol ($x10^6$ L)	Plutonium (g)
January 1967	1.23	71
February	1.19	167
March	1.04	102
April	1.16	124
May	0.94	111
June	1.09	145
July	1.03	46
August	1.01	124
September	0.959	38
October	0.798	25
November	0.764	52
December	0.478	30
12-mo Total	(11.689)	(1,035)
TOTAL FROM 3/59	241.82	20,945
January 1968	0.483	133
February	0.504	62
March	0.469	49
April	0.526	48
May	0.689	58
June	0.772	43
July	0.246	34
August	0.570	32
September	0.213	46
October	0.338	43
November	0.530	101
December	0.530	31
12-mo Total	(5.87)	(680)
TOTAL FROM 3/59	247.7	21,625

Period	Vol ($x10^6$L)	Plutonium (g)
January 1969	0.242	27
February	0.151	2
March	0.738	14
April	0.515	31.8
May	0.806	78
June	0.485	77.5
July	0.363	43.8
August	0.522	21.8
September	0.651	37.3
October	0.651	70
November	0.522	51.4
December	0.784	62.5
12-mo Total	(6.43)	(517.1)
TOTAL FROM 3/59	254.1	22,142
January 1970	0.348	64.6
February	0.344	54.3
March	0.356	48
April	0.428	15.8
May	0.121	24.7
June	0.132	28.2
July	0.204	19.5
August	0.182	38.5
September	0.299	57.5
October	0.371	107.2
November	0.466	88.7
December	0.197	103
12-mo Total	(3.448)	(650)
TOTAL FROM 3/59	257.55	22,792

Period	Vol ($\times 10^6$ L)	Plutonium (g)
January 1971	0.216	54.0
February	0.181	66.81
March	0.286	88.36
April	0.659	136.4
May	0.739	152.0
June	0.950	102.0
July	0.713	87.93
August	0.872	94.90
September	0.870	139.1
October	0.768	33.08
November	0.863	68.89
December	1.067	43.11
12-mo Total	(8.18)	(1,066.5)
TOTAL FROM 3/59	265.73	23,858
January 1972	1.17	94
February	0.791	40
March	0.898	49
April	1.21	76
May	1.40	230
June	1.16	86.9
July	0.762	94.0
August	1.24	81.0
September	0.867	16.0
October	0.689	33.0
November	0.784	76.0
December	0.713	63.0
12-mo Total	(11.7)	(939.0)
TOTAL FROM 3/59	278	24,800

Period	Vol ($\times 10^6$ L)	Plutonium (g)
January 1973	0.571	42.0
February	0.752	52.0
March	1.22	62.0
April	0.820	88.0
May	0.101	83.0
12-mo Total	(3.47)	(327)
TOTAL FROM 3/59	281	25,100

APPENDIX B

SOURCES OF AQUEOUS WASTE TO THE D-4, D-5, AND D-6 DRAIN SYSTEMS

(From a report by R. E. Van der Cook on the use of 216-Z-12 Crib.)

D-4 DRAIN SYSTEM

This system serves the Plutonium Chemistry Laboratory and special purpose process hoods.

Location	Use	Quantity Liters/Month Average	Remarks
Room 179-A	Floor drains	Normally none	Not normally contaminated.
Room 179-B	Special plutonium processing	Variable	2 liters/minute when used.
Hood 55	Condenser cooling and condensate	Variable	2 liters/minute when used.
Hood 51	Condenser water	Variable	2 liters/minute when used.
Ion exchange	Waste	Variable	
Hood 60	Drain	<1,000	
Hood 57	Drain	Normally none	
Room floor	Drain	Normally none	
Room 179	Sink drain Hood 14 drain Hood 1-B drain Hood 1-C drain Condenser cooling water, hood 14 Hood 4 drain Aspirator drain, hood 4		
	Total	<10,000	
Room 183-A	Floor drain	Normally none	Safety shower

D-4 DRAIN SYSTEM (continued)

Location	Use	Quantity Liters/Month Average	Remarks
Rooms 185, 186, and 188	Sink drain	1,000	
	Open face hood drain	1,000	
	Floor drain	Normally none	Safety shower
	Tocco unit	10,000	Based on 1 day/week use. Not contaminated.
	Electro-dryer		Not currently used.
	Gloved hood drains		For emergency use to prevent water flooding.
Room 189	Hood drain		Not in use.
Room 191	Sink drains	2,000	
TOTAL Not Contaminated		10,000	
TOTAL Contaminated		15,000	
Overall Usage		25,000	

D-5 DRAIN SYSTEM

This drain system serves the Analytical Laboratory Area. Usages are listed in the following table. All streams carry plutonium contamination unless otherwise indicated.

Location	Use	Quantity Liters/Month Average	Remarks
Room 126	Personnel decontamination sink and shower	<1,000	Intermittent use
Corridor 4-A	Wound flushing sink	10	
Room 133	Film washing	22,000	Not contaminated
Room 134	Condenser	8,000	Not contaminated
Rooms 134, 135, and 136	Laboratory sinks	1,000	Occasional use only.
	Fluoride, chloride, and nitrogen still condensers	20,000	Used about 6 days/month. Contamination only in event of glassware failure (500 mg maximum).
	Sample slurping 125 liters per month	6,000	Assumed 50:1 dilution.
Room 143	Glassware washing	10,000	
Rooms 152-157	Hood sinks	1,000	
Room 145	Hood drains and sinks	2,000	Plutonium Chemistry Laboratory operations.
Corridors 4-B and C	Safety shower drains		
TOTAL Not Contaminated		30,000	
TOTAL Contaminated		40,000	
Overall Usage		70,000	

D-6 SYSTEM

Location	Use	Quantity Liters/Month Average	Remarks
Room 233	Hood 9-A off-gas jet		20 to 30 liters/minute when used.
Room 232	Floor drain		
Room 328	Personnel decontamination sink		On third floor.
Room 230	HC-20 cooling water		20 to 30 liters/minute when used. Not contaminated.
Room 228	Sink drain	Variable	Intermittent
	Hood 9 off-gas jet	600,000	20 to 30 liters/minute when used. 0.06 M HF. 300 hours/month (6-month average).
Room 227	Hood drain		Water is not currently used in this hood.
	Sink is duct level	Variable	Intermittent use.
Room 158	Instrument shop sink	1,000	Not contaminated.
Room 159	Hood sink	100	Instrument cleaning.
Corridor #5	Water fountain	1,000	Not contaminated.
Room 171	Floor drain		
Room 170	Hood drain	1,000	Decontamination of shipping bottles.
Rooms 221 and 129	Several drains		Not currently used.
TOTAL		603,000	

D-6 SYSTEM (Continued)

Location	Use	Quantity Liters/Month Average	Remarks
Plutonium Reclamation Facility			
Steam condensate from continuous dissolvers		3,000	
Scrubber solution tanks 10 and 12			Currently recycled to process.
Supernate evaporator steam condensate		7,000	
Process condensate from supernate		5,000	
Product concentrator steam condensate		1,000	
Plutonium reclamation decontamination hood		1,000	
Hot maintenance hood		100	
Exhaust plenum jet			Potential cross connection to D-3 drain.
Incinerator, 232-Z Building	Scrubber solution	2,000	Contains 50 grams plutonium.
	Leach hood drain	Variable	Not normally used.
Waste Treatment	ICW	25,000	
	Resin wash	2,000	
TOTAL Plutonium Reclamation Facility, Incinerator, Waste Treatment		46,000	

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APPENDIX C

ANALYTICAL RESULTS FOR PLUTONIUM AND AMERICIUM ACTIVITY

This appendix presents results of all plutonium and americium analyses conducted on 216-Z-12 Crib sediment samples and used in interpretation of the distribution of plutonium. Reported activities in picocuries per gram for ^{238}Pu, $^{239,240}Pu$, and ^{241}Am are listed for each well with depth. The confidence in the analytical value, reported as the counting standard deviation (1σ), is listed with the analytical data. The counting standard deviation is based primarily on counting statistics and as such should not be taken as an estimate of the true sample variability. The data are differentiated as to "real" and "less than" values. A less than value is defined as a reported analytical value that is zero within the confidence interval defined by three counting standard deviations. To aid in quick identification, the confidence interval for a less than value is reported using scientific notation, while the confidence interval for a real value is reported as a percentage of the analytical result. Data are identified as to laboratory. Rockwell Hanford Operations (Rockwell) analyses were performed by the Field Support Unit of the Environmental Technologies Group using a Si(Li) detector system. Results reported by Eberline Instrument Corporation (Eberline) and LFE Environmental Analysis Laboratory (LFE) were performed using alpha energy analysis. The analytical results for Wells 152 and 153, obtained by the 1976 field study and reported in Table C-1, are also listed and identified with the notation (o) following the laboratory identification.

The laboratories were instructed to analyze the sediment samples as provided. As part of their standard procedure, LFE sieved a number of samples to remove material larger than 2 mm in diameter. Finer material has a larger surface area per unit weight, which favors sorption reactions. In the 216-Z-1A Crib, higher activity of plutonium and americium was generally associated with the finer material. Sieving of a sample to remove coarse material thus could bias the results and interpretation of plutonium distribution. These samples are identified with the notation (s) following the laboratory designation.

TABLE C-1. Analytical Results for Wells 299-W18-152 and 299-W18-153.

Depth [m (ft)]	^{239}Pu nCi/g of soil
Well 299-W18-152	
4.27 (14)	$8.00 \times 10^{-4} \pm 5.50 \times 10^{-5}$
7.62 (25)	2.25×10^{-2}
10.06 (33)	$4.23 \times 10^{-4} \pm 5.63 \times 10^{-5}$
13.41 (44)	$3.47 \times 10^{-4} \pm 3.12 \times 10^{-5}$
16.75 (55)	$3.83 \times 10^{-4} \pm 4.98 \times 10^{-5}$
21.34 (70)	$2.39 \times 10^{-3} \pm 1.67 \times 10^{-4}$
26.21 (86)	$8.38 \times 10^{-4} \pm 7.54 \times 10^{-5}$
29.87 (98)	$3.38 \times 10^{-4} \pm 4.73 \times 10^{-5}$
33.07 (108.5)	$9.23 \times 10^{-4} \pm 8.31 \times 10^{-5}$
34.29 (112.5)	$2.34 \times 10^{-2} \pm 3.98 \times 10^{-3}$
Well 299-W18-153	
6.4 (21)	1.18×10^{-1}
9.1 (30)	$4.28 \times 10^{-3} \pm 3.00 \times 10^{-4}$
12.2 (40)	1.16×10^{-3}
15.2 (50)	$5.41 \times 10^{-4} \pm 3.78 \times 10^{-5}$
18.3 (60)	$1.13 \times 10^{-3} \pm 1.01 \times 10^{-4}$
24.4 (80)	$2.03 \times 10^{-4} \pm 2.23 \times 10^{-5}$
26.8 (88)	$5.00 \times 10^{-4} \pm 3.00 \times 10^{-5}$
28.7 (94)	$4.50 \times 10^{-4} \pm 5.86 \times 10^{-5}$
31.7 (104)	$9.05 \times 10^{-4} \pm 5.43 \times 10^{-5}$
33.2 (109)	$4.37 \times 10^{-4} \pm 3.50 \times 10^{-5}$

TABLE C-2. Plutonium and Americium Activity in Well 299-W18-152.

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
1.52	LFE	$7 \times 10^{-4} \pm 2 \times 10^{-3}$	$3.8 \times 10^{-3} \pm 1.6 \times 10^{-3}$	$1 \times 10^{-3} \pm 3 \times 10^{-3}$
4.27	LFE(o)	---	$8.0 \times 10^{-1} \pm 6.9\%$	---
6.10	LFE	$3.3 \times 10^{-3} \pm 1.5 \times 10^{-3}$	$1.01 \times 10^{-2} \pm 16.8\%$	$2.9 \times 10^{-3} \pm 1.4 \times 10^{-3}$
7.62	LFE(o)	---	$2.25 \times 10^{+1} \pm 5\%$	---
	LFE	$3.85 \times 10^{-1} \pm 4.2\%$	$2.07 \times 10^{+1} \pm 2.4\%$	$3.86 \times 10^{0} \pm 2.6\%$
	EIC	$4.99 \times 10^{-1} \pm 17.6$	$1.91 \times 10^{+1} \pm 9.2\%$	$2.90 \times 10^{0} \pm 8.5\%$
9.14	LFE	$2.6 \times 10^{-3} \pm 1.6 \times 10^{-3}$	$5.2 \times 10^{-2} \pm 7.7\%$	$4.0 \times 10^{-1} \pm 3.5\%$
10.06	LFE(o)	---	$4.23 \times 10^{-1} \pm 13.3\%$	---
10.67	LFE(s)	$5 \times 10^{-4} \pm 9 \times 10^{-4}$	$6.4 \times 10^{-2} \pm 4.7\%$	$8.0 \times 10^{-1} \pm 2.5\%$
12.65	LFE(s)	$1.0 \times 10^{-3} \pm 3 \times 10^{-3}$	$1.11 \times 10^{-1} \pm 7.2\%$	$1.5 \times 10^{-2} \pm 13.3\%$
13.41	LFE(o)	---	$3.47 \times 10^{-1} \pm 9\%$	---
	LFE(s)	$9 \times 10^{-3} \pm 22.2\%$	$2.1 \times 10^{-1} \pm 4.3\%$	$1.3 \times 10^{-2} \pm 15.4\%$
16.76	LFE(o)	---	$3.83 \times 10^{-1} \pm 13\%$	---
19.66	LFE(s)	$0 \pm 3 \times 10^{-3}$	$5.5 \times 10^{-2} \pm 12.7\%$	$2.1 \times 10^{-3} \pm 1.9 \times 10^{-3}$
21.34	LFE(o)	---	$2.39 \times 10^{0} \pm 7\%$	---
26.21	LFE(o)	---	$8.38 \times 10^{-1} \pm 9\%$	---
26.82	LFE	$3.8 \times 10^{-3} \pm 1.5 \times 10^{-3}$	$1.43 \times 10^{-1} \pm 3.5\%$	$1.1 \times 10^{-2} \pm 27.3\%$
29.87	LFE(o)	---	$3.38 \times 10^{-1} \pm 14.0\%$	---
32.46	LFE(s)	$5.6 \times 10^{-3} \pm 21.4\%$	$1.04 \times 10^{-1} \pm 3.8\%$	$2.4 \times 10^{-3} \pm 1.6 \times 10^{-3}$
33.07	LFE(o)	---	$9.23 \times 10^{-4} \pm 9\%$	---
	LFE	$1.06 \times 10^{-3} \pm 9 \times 10^{-4}$	$7.9 \times 10^{-2} \pm 3.8\%$	$-4 \times 10^{-4} \pm 1.3 \times 10^{-3}$
34.29	LFE(o)	---	$2.34 \times 10^{+1} \pm 17.0\%$	---
	LFE(s)	$3 \times 10^{-3} \pm 2 \times 10^{-3}$	$1.94 \times 10^{-1} \pm 4.1\%$	$6 \times 10^{-3} \pm 3 \times 10^{-3}$
	LFE	$5 \times 10^{-3} \pm 2 \times 10^{-3}$	$4.4 \times 10^{-3} \pm 31.8\%$	$1.0 \times 10^{-2} \pm 4 \times 10^{-3}$
34.44	LFE(s)	$3 \times 10^{-3} \pm 5 \times 10^{-3}$	$7.7 \times 10^{-2} \pm 13.0\%$	$1.6 \times 10^{-2} \pm 6 \times 10^{-6}$

TABLE C-3. Plutonium and Americium Activity in Well 299-W18-153.

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
1.52	EIC	$1.49 \times 10^{-2} \pm 1.50 \times 10^{-2}$	$1.94 \times 10^{-1} \pm 9.5 \times 10^{-2}$	$3.04 \times 10^{-2} \pm 5.0 \times 10^{-2}$
6.10	EIC	$4.25 \times 10^{-2} \pm 3.99 \times 10^{-2}$	$6.37 \times 10^{-2} \pm 3.72 \times 10^{-2}$	$5.15 \times 10^{-2} \pm 3.03 \times 10^{-2}$
	EIC	$3.01 \times 10^{-3} \pm 1.38 \times 10^{-2}$	$4.57 \times 10^{-2} \pm 2.43 \times 10^{-2}$	$1.01 \times 10^{-1} \pm 24.7\%$
6.40	LFE(o)	---	$1.18 \times 10^{+2} \pm 5\%$	---
	LFE	$2.4 \times 10^{-1} \pm 16.7\%$	$1.30 \times 10^{-1} \pm 3.1\%$	$5.2 \times 10^{0} \pm 5.8\%$
	EIC	$2.60 \times 10^{0} \pm 10.8\%$	$1.25 \times 10^{+2} \pm 8.5\%$	$3.17 \times 10^{+1} \pm 4.5\%$
7.62	EIC	$6.72 \times 10^{-2} \pm 3.23 \times 10^{-2}$	$2.03 \times 10^{0} \pm 11.9\%$	$7.57 \times 10^{-1} \pm 13.5\%$
8.23	EIC	$6.95 \times 10^{-2} \pm 3.89 \times 10^{-2}$	$2.62 \times 10^{0} \pm 10.5\%$	$1.98 \times 10^{0} \pm 7.4\%$
9.14	LFE(o)	---	$4.28 \times 10^{0} \pm 7\%$	---
	EIC	$1.53 \times 10^{-1} \pm 30.5\%$	$3.35 \times 10^{0} \pm 9.5\%$	$2.14 \times 10^{0} \pm 7.9\%$
12.19	LFE(o)	---	1.16×10^{0}	---
	EIC	$1.84 \times 10^{-2} \pm 2.91 \times 10^{-2}$	$1.01 \times 10^{-1} \pm 3.41 \times 10^{-2}$	$8.19 \times 10^{-1} \pm 11.8\%$
15.24	LFE(o)	---	$5.41 \times 10^{-1} \pm 7\%$	---
16.76	EIC	$3.27 \times 10^{-2} \pm 3.29 \times 10^{-2}$	$-1.64 \times 10^{-2} \pm 6.36 \times 10^{-2}$	$1.45 \times 10^{-1} \pm 26.2\%$
18.29	LFE(o)	---	$1.13 \times 10^{0} \pm 8.9\%$	---
	EIC	$-1.85 \times 10^{-2} \pm 2.93 \times 10^{-2}$	$1.85 \times 10^{-2} \pm 2.27 \times 10^{-2}$	$4.35 \times 10^{-1} \pm 13.9\%$
22.25	EIC	$-2.08 \times 10^{-2} \pm 2.09 \times 10^{-2}$	$2.08 \times 10^{-2} \pm 5.1 \times 10^{-2}$	$5.44 \times 10^{-1} \pm 12.4\%$
24.38	LFE(o)	---	$2.03 \times 10^{-1} \pm 11\%$	---
	EIC	$2.40 \times 10^{-2} \pm 2.89 \times 10^{-2}$	$2.40 \times 10^{-2} \pm 1.80 \times 10^{-2}$	$5.45 \times 10^{-2} \pm 2.08 \times 10^{-2}$
26.82	LFE(o)	---	$5.00 \times 10^{-1} \pm 6\%$	---
28.65	LFE(o)	---	$4.50 \times 10^{-1} \pm 13.0\%$	---
30.48	EIC	$3.45 \times 10^{-2} \pm 2.50 \times 10^{-2}$	$4.14 \times 10^{-2} \pm 1.97 \times 10^{-2}$	$1.39 \times 10^{-2} \pm 1.39 \times 10^{-2}$
31.70	LFE(o)	---	$9.05 \times 10^{-1} \pm 6\%$	---
32.61	EIC	$4.64 \times 10^{-2} \pm 3.37 \times 10^{-2}$	$4.64 \times 10^{-2} \pm 3.1 \times 10^{-2}$	$8.21 \times 10^{-3} \pm 2.46 \times 10^{-2}$
33.22	LFE(o)	---	$4.37 \times 10^{-1} \pm 8.0\%$	---

TABLE C-4. Plutonium and Americium Activity in Well 299-W18-154.

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
4.57	Rockwell	---	<2,000	<200
	Rockwell	---	<2,000	<200
5.03	Rockwell	---	<2,000	<200
	Rockwell	---	<2,000	<200
5.49	Rockwell	---	$2.27 \times 10^{5} \pm 25\%$	$1.86 \times 10^{2} \pm 15\%$
	Rockwell	---	$2.52 \times 10^{5} \pm 15\%$	$1.96 \times 10^{2} \pm 15\%$
	Rockwell	---	$1.82 \times 10^{5} \pm 30\%$	$1.96 \times 10^{2} \pm 15\%$
6.10	Rockwell	---	<2,000	<200

TABLE C-5. Plutonium and Americium Activity in Well 299-W18-157.

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
16.46	LFE	$5.5 \times 10^{-3} \pm 1.8 \times 10^{-3}$	$5.5 \times 10^{-3} \pm 29.1\%$	$2 \times 10^{-3} \pm 7 \times 10^{-3}$
	EIC	$1.29 \times 10^{-2} \pm 1.07 \times 10^{-2}$	$1.08 \times 10^{-2} \pm 1.06 \times 10^{-2}$	$5.01 \times 10^{-2} \pm 4.02 \times 10^{-2}$
18.29	LFE	$7.0 \times 10^{-3} \pm 22.9\%$	$4.6 \times 10^{-3} \pm 28.3\%$	$1.5 \times 10^{-3} \pm 1.8 \times 10^{-3}$
	EIC	$3.15 \times 10^{-2} \pm 2.11 \times 10^{-2}$	$4.20 \times 10^{-2} \pm 1.68 \times 10^{-2}$	$3.29 \times 10^{-2} \pm 2.02 \times 10^{-2}$
19.81	EIC	$1.20 \times 10^{-2} \pm 1.20 \times 10^{-2}$	$8.99 \times 10^{-2} \pm 3.88 \times 10^{-2}$	$1.13 \times 10^{-1} \pm 3.44 \times 10^{-2}$
22.25	LFE	$4.27 \times 10^{-3} \pm 1.7 \times 10^{-3}$	$1.4 \times 10^{-3} \pm 1.1 \times 10^{-3}$	$-7 \times 10^{-3} \pm 5 \times 10^{-3}$
	EIC	$-1.39 \times 10^{-2} \pm 2.95 \times 10^{-2}$	$1.87 \times 10^{-1} \pm 23.6\%$	$4.14 \times 10^{-2} \pm 7.75 \times 10^{-2}$
22.86	EIC	$2.42 \times 10^{-2} \pm 1.09 \times 10^{-2}$	$3.87 \times 10^{-1} \pm 13.3\%$	$1.95 \times 10^{-1} \pm 23.2\%$
24.23	EIC	$2.24 \times 10^{-2} \pm 2.75 \times 10^{-2}$	$8.97 \times 10^{-2} \pm 4.56 \times 10^{-2}$	$5.41 \times 10^{-2} \pm 4.73 \times 10^{-2}$
24.38	LFE	$7.0 \times 10^{-3} \pm 28.6\%$	$7 \times 10^{-3} \pm 28.6\%$	$2.9 \times 10^{-3} \pm 1.2 \times 10^{-3}$
	EIC	$-7.78 \times 10^{-3} \pm 1.74 \times 10^{-2}$	$2.18 \times 10^{-2} \pm 1.16 \times 10^{-2}$	$5.13 \times 10^{-2} \pm 4.07 \times 10^{-2}$
25.30	EIC	$2.98 \times 10^{-2} \pm 2.31 \times 10^{-2}$	$1.79 \times 10^{-2} \pm 2.3 \times 10^{-2}$	$2.95 \times 10^{-2} \pm 4.72 \times 10^{-2}$
30.48	LFE	$2.0 \times 10^{-3} \pm 1.1 \times 10^{-3}$	$2.6 \times 10^{-3} \pm 9 \times 10^{-4}$	$3.2 \times 10^{-2} \pm 12.5\%$
	EIC	$7.35 \times 10^{-2} \pm 3.2 \times 10^{-2}$	$1.84 \times 10^{-2} \pm 1.85 \times 10^{-2}$	$6.42 \times 10^{-1} \pm 14.7\%$
31.09	LFE(s)	$1.6 \times 10^{-3} \pm 1.2 \times 10^{-3}$	$1.4 \times 10^{-3} \pm 8 \times 10^{-4}$	$1 \times 10^{-3} \pm 4 \times 10^{-3}$
	EIC	$-4.9 \times 10^{-3} \pm 1.64 \times 10^{-2}$	$1.67 \times 10^{-1} \pm 25.7\%$	$8.70 \times 10^{-2} \pm 2.80 \times 10^{-2}$
31.39	LFE	$5.2 \times 10^{-3} \pm 23.1\%$	$1.5 \times 10^{-3} \pm 7 \times 10^{-4}$	$4.0 \times 10^{-3} \pm 2 \times 10^{-3}$
32.00	LFE(s)	$2.5 \times 10^{-3} \pm 1.4 \times 10^{-3}$	$-4 \times 10^{-4} \pm 1.1 \times 10^{-3}$	$9 \times 10^{-4} \pm 2.1 \times 10^{-3}$

TABLE C-6. Plutonium and Americium Activity in Well 299-W18-162.

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
5.03	Rockwell	---	<2,000	<300
5.63	Rockwell	---	$1.02 \times 10^{+6} \pm 5.05 \times 10^{+5}$	$1.67 \times 10^{+5} \pm 30\%$
5.90	Rockwell	---	$4.97 \times 10^{+6} \pm 10\%$	$9.65 \times 10^{+5} \pm 10\%$
	Rockwell	---	$4.48 \times 10^{+6} \pm 10\%$	$9.22 \times 10^{+5} \pm 10\%$
6.23	Rockwell	---	$3.62 \times 10^{+6} \pm 15\%$	$7.34 \times 10^{+5} \pm 10\%$
7.04	Rockwell	---	<2,000	<300
7.97	Rockwell	---	<2,000	<300
8.84	Rockwell	---	<2,000	<300

TABLE C-7. Plutonium and Americium Activity in Well 299-W18-179 (Sheet 1 of 2).

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
1.22	EIC	$2.59 \times 10^{-2} \pm 1.60 \times 10^{-2}$	$4.53 \times 10^{-2} \pm 3.73 \times 10^{-2}$	$3.45 \times 10^{-1} \pm 18.4\%$
2.44	EIC	$-2.74 \times 10^{-2} \pm 2.11 \times 10^{-2}$	$2.68 \times 10^{-1} \pm 16.8\%$	$1.73 \times 10^{-1} \pm 6.1 \times 10^{-2}$
3.05	LFE	$1.3 \times 10^{-3} \pm 1.6 \times 10^{-3}$	$1.0 \times 10^{-2} \pm 20\%$	$1 \times 10^{-3} \pm 4 \times 10^{-3}$
	EIC	$2.07 \times 10^{-2} \pm 1.83 \times 10^{-2}$	$7.59 \times 10^{-2} \pm 2.55 \times 10^{-2}$	$6.66 \times 10^{-2} \pm 4.02 \times 10^{-2}$
3.66	EIC	$1.24 \times 10^{-2} \pm 1.85 \times 10^{-2}$	$5.18 \times 10^{-2} \pm 3.44 \times 10^{-2}$	$5.7 \times 10^{-2} \pm 3.52 \times 10^{-2}$
4.27	EIC	$3.05 \times 10^{-2} \pm 2.70 \times 10^{-2}$	$2.54 \times 10^{-2} \pm 1.47 \times 10^{-2}$	$5.17 \times 10^{-2} \pm 5.20 \times 10^{-2}$
4.57	LFE	$3.3 \times 10^{-3} \pm 1.8 \times 10^{-3}$	$1.3 \times 10^{-2} \pm 23\%$	$2 \times 10^{-3} \pm 4 \times 10^{-3}$
	EIC	$1.12 \times 10^{-2} \pm 7.9 \times 10^{-3}$	$7.81 \times 10^{-2} \pm 2.88 \times 10^{-2}$	$1.08 \times 10^{-2} \pm 4.45 \times 10^{-2}$
4.88	LFE	$2.5 \times 10^{-2} \pm 16\%$	$1.86 \times 10^{-2} \pm 5.9\%$	$1.46 \times 10^{-1} \pm 4.1\%$
	EIC	$3.07 \times 10^{-2} \pm 2.18 \times 10^{-2}$	$1.69 \times 10^{-1} \pm 26\%$	$9.65 \times 10^{-2} \pm 3.27 \times 10^{-2}$
5.18	Rockwell	---	$1.04 \times 10^{6} \pm 20\%$	$4.32 \times 10^{5} \pm 15\%$
5.33	Rockwell	---	$2.04 \times 10^{4} \pm 20\%$	$5.86 \times 10^{3} \pm 20\%$
	Rockwell	---	$1.96 \times 10^{4} \pm 20\%$	$5.86 \times 10^{3} \pm 20\%$
6.71	EIC	$1.24 \times 10^{+1} \pm 7.5\%$	$5.56 \times 10^{+2} \pm 7.1\%$	$1.96 \times 10^{+2} \pm 11.2\%$
	EIC	$1.53 \times 10^{+1} \pm 8\%$	$6.75 \times 10^{+2} \pm 7.6\%$	$1.83 \times 10^{+2} \pm 8.4\%$
	EIC	$8.88 \times 10^{0} \pm 10.7\%$	$3.98 \times 10^{+2} \pm 10.0\%$	$2.34 \times 10^{+2} \pm 7.6\%$
7.62	EIC	$3.54 \times 10^{-1} \pm 18\%$	$1.41 \times 10^{+1} \pm 8.4\%$	$1.59 \times 10^{+1} \pm 9.7\%$
8.53	EIC	$2.33 \times 10^{-1} \pm 24.5\%$	$8.60 \times 10^{0} \pm 9.6\%$	$1.32 \times 10^{+1} \pm 8.0\%$
9.14	EIC	$9.16 \times 10^{-2} \pm 3.15 \times 10^{-2}$	$1.94 \times 10^{0} \pm 11.1\%$	$2.14 \times 10^{0} \pm 11.6\%$
10.67	EIC	$3.33 \times 10^{-2} \pm 1.94 \times 10^{-2}$	$2.89 \times 10^{-1} \pm 25.3\%$	$6.02 \times 10^{-1} \pm 15.4\%$
10.97	EIC	$1.3 \times 10^{-1} \pm 1.6 \times 10^{-1}$	$1.67 \times 10^{-1} \pm 9.2 \times 10^{-2}$	$2.48 \times 10^{-1} \pm 8.6 \times 10^{-2}$
12.19	EIC	$1.09 \times 10^{-1} \pm 28.2\%$	$1.27 \times 10^{0} \pm 9.7\%$	$8.26 \times 10^{-1} \pm 16.4\%$

TABLE C-7. Plutonium and Americium Activity in Well 299-W18-179 (Sheet 2 of 2).

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
12.80	LFE(s)	$1.14 \times 10^{-1} \pm 9.6\%$	$4.78 \times 10^{0} \pm 3.1\%$	$2.29 \times 10^{0} \pm 3.5\%$
	LFE(s)	$7.4 \times 10^{-2} \pm 12.2\%$	$3.36 \times 10^{0} \pm 3.0\%$	$1.82 \times 10^{0} \pm 3.9\%$
	LFE(s)	$1.08 \times 10^{-1} \pm 11.1\%$	$3.49 \times 10^{0} \pm 3.2\%$	$2.07 \times 10^{0} \pm 4.3\%$
	EIC	$7.03 \times 10^{-2} \pm 29.6\%$	$7.17 \times 10^{-1} \pm 10.1\%$	$4.72 \times 10^{-1} \pm 19.5\%$

TABLE C-8. Plutonium and Americium Activity in Well 299-W18-180.

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
5.79	Rockwell	---	<2,000	<300
	LFE	$1.1 \times 10^{-2} \pm 27.3\%$	$6.1 \times 10^{-2} \pm 8.2\%$	$1.23 \times 10^{0} \pm 3.2\%$
	EIC	$2.03 \times 10^{-2} \pm 1.8 \times 10^{-2}$	$1.49 \times 10^{-1} \pm 5.9 \times 10^{-2}$	$7.47 \times 10^{-1} \pm 15.2\%$
6.71	Rockwell	---	<2,000	<300
	LFE	$1.8 \times 10^{-2} \pm 22.2\%$	$9.0 \times 10^{-1} \pm 4.4\%$	$2.79 \times 10^{-1} \pm 3.9\%$
	EIC	$-6.12 \times 10^{-2} \pm 4.35 \times 10^{-2}$	$5.66 \times 10^{-1} \pm 15.1\%$	$2.52 \times 10^{-1} \pm 23.3\%$
8.08	Rockwell	---	<2,000	<300
	LFE	$2.58 \times 10^{-1} \pm 4.3\%$	$1.27 \times 10^{+1} \pm 2.4\%$	$2.33 \times 10^{0} \pm 2.6\%$
	EIC	$2.22 \times 10^{-1} \pm 14.6\%$	$1.2 \times 10^{+1} \pm 5.6\%$	$2.09 \times 10^{0} \pm 9.8\%$
8.23	Rockwell	---	<2,000	<300
	LFE	$2.80 \times 10^{-1} \pm 4.6\%$	$1.35 \times 10^{+1} \pm 2.2\%$	$2.69 \times 10^{0} \pm 2.6\%$
	EIC	$3.25 \times 10^{-1} \pm 16.4\%$	$1.36 \times 10^{+1} \pm 7.3\%$	$2.32 \times 10^{0} \pm 8.7\%$
8.84	Rockwell	---	<2,000	<300
9.14	EIC	$1.49 \times 10^{-2} \pm 2.07 \times 10^{-2}$	$4.70 \times 10^{-1} \pm 16.4\%$	$2.91 \times 10^{-1} \pm 21.1\%$
9.45	Rockwell	---	<2,000	<300
10.67	Rockwell	---	<2,000	<300
	EIC	$-9.32 \times 10^{-3} \pm 1.6 \times 10^{-2}$	$9.32 \times 10^{-2} \pm 4.81 \times 10^{-2}$	$5.05 \times 10^{-1} \pm 29.7\%$
11.58	Rockwell	---	<2,000	<300
11.89	Rockwell	---	<2,000	<300
12.19	Rockwell	---	<2,000	<300
	LFE(s)	$1.8 \times 10^{-2} \pm 27.8\%$	$4.4 \times 10^{-1} \pm 4.5\%$	$8.5 \times 10^{-1} \pm 3.5\%$
	EIC	$4.17 \times 10^{-2} \pm 5.4 \times 10^{-2}$	$-5.56 \times 10^{-2} \pm 7.63 \times 10^{-2}$	$5.47 \times 10^{-1} \pm 17.2\%$

TABLE C-9. Plutonium and Americium Activity in Well 299-W18-181 (Sheet 1 of 5).

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
3.66	Rockwell	---	<2,000	<300
4.57	LFE	$2.4 \times 10^{-3} \pm 1.6 \times 10^{-3}$	$6.0 \times 10^{-3} \pm 2 \times 10^{-3}$	$5.0 \times 10^{-3} \pm 1.8 \times 10^{-3}$
5.18	Rockwell	---	<2,000	<300
5.87	Rockwell	---	$2.89 \times 10^{6} \pm 25\%$	$8.30 \times 10^{5} \pm 10\%$
	Rockwell		$2.95 \times 10^{6} \pm 25\%$	$9.52 \times 10^{5} \pm 10\%$
5.93	Rockwell	---	$4.49 \times 10^{6} \pm 25\%$	$9.26 \times 10^{5} \pm 10\%$
	Rockwell	---	$4.34 \times 10^{6} \pm 30\%$	$7.86 \times 10^{5} \pm 12\%$
5.99	Rockwell	---	$2.58 \times 10^{6} \pm 15\%$	$4.84 \times 10^{5} \pm 15\%$
	Rockwell	---	$2.24 \times 10^{6} \pm 15\%$	$4.73 \times 10^{5} \pm 15\%$
6.25	Rockwell	---	$4.88 \times 10^{6} \pm 5\%$	$7.72 \times 10^{5} \pm 10\%$
	Rockwell	---	$4.88 \times 10^{6} \pm 5\%$	$9.01 \times 10^{5} \pm 10\%$
6.56	Rockwell	---	$9.24 \times 10^{5} \pm 15\%$	$2.32 \times 10^{5} \pm 15\%$
	Rockwell	---	$9.50 \times 10^{5} \pm 5\%$	$1.96 \times 10^{5} \pm 15\%$
6.43 to 6.80	Rockwell	---	$1.07 \times 10^{6} \pm 8\%$	$2.44 \times 10^{5} \pm 15\%$
6.62	Rockwell	---	$1.23 \times 10^{6} \pm 10\%$	$2.91 \times 10^{5} \pm 15\%$
6.68	Rockwell	---	$9.76 \times 10^{5} \pm 5\%$	$2.62 \times 10^{5} \pm 15\%$
6.74	Rockwell	---	$7.08 \times 10^{5} \pm 15\%$	$2.56 \times 10^{5} \pm 15\%$
6.80	Rockwell	---	$1.17 \times 10^{6} \pm 5\%$	$2.74 \times 10^{5} \pm 15\%$
6.93	Rockwell	---	$3.49 \times 10^{4} \pm 25\%$	$9.67 \times 10^{3} \pm 20\%$
	Rockwell	---	$9.13 \times 10^{3} \pm 25\%$	$1.60 \times 10^{3} \pm 25\%$
6.99	Rockwell	---	$4.79 \times 10^{3} \pm 25\%$	$9.50 \times 10^{2} \pm 25\%$
7.05	Rockwell	---	$4.49 \times 10^{3} \pm 25\%$	$8.80 \times 10^{2} \pm 25\%$

TABLE C-9. Plutonium and Americium Activity in Well 299-W18-181 (Sheet 2 of 5).

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
7.08	Rockwell	---	$5.09 \times 10^{3} \pm 25\%$	$9.50 \times 10^{2} \pm 25\%$
7.11	Rockwell	---	<2,000	$2.3 \times 10^{2} \pm 30\%$
8.69	Rockwell	---	<2,000	<300
	LFE	$6.7 \times 10^{-2} \pm 6.0\%$	$2.90 \times 10^{0} \pm 2.4\%$	$2.62 \times 10^{-1} \pm 3.8\%$
	EIC	$5.20 \times 10^{-2} \pm 2.93 \times 10^{-2}$	$1.06 \times 10^{0} \pm 10.3\%$	$1.64 \times 10^{0} \pm 8.7\%$
10.06	Rockwell	---	<2,000	<300
10.67	Rockwell	---	<2,000	<300
	LFE(s)	$4.93 \times 10^{0} \pm 2.84\%$	$2.42 \times 10^{2} \pm 2.9\%$	$5.86 \times 10^{1} \pm 2.6\%$
	EIC	$3.12 \times 10^{0} \pm 9\%$	$1.48 \times 10^{2} \pm 7.7\%$	$3.60 \times 10^{1} \pm 8.8\%$
	EIC	$1.79 \times 10^{0} \pm 7.2\%$	$8.10 \times 10^{1} \pm 5.4\%$	$3.80 \times 10^{1} \pm 6.6\%$
10.97	Rockwell	---	<2,000	<300
11.28	Rockwell	---	<2,000	<300
11.89	Rockwell	---	<2,000	<300
12.19	Rockwell	---	<2,000	<300
	LFE(s)	$3.66 \times 10^{0} \pm 2.7\%$	$1.84 \times 10^{2} \pm 2.2\%$	$5.25 \times 10^{1} \pm 3.0\%$
	EIC	$1.68 \times 10^{0} \pm 10.9\%$	$8.17 \times 10^{+1} \pm 8\%$	$1.46 \times 10^{1} \pm 6.0\%$
12.80	Rockwell	---	<2,000	<300
13.41	Rockwell	---	<2,000	<300
13.72	Rockwell	---	<2,000	<300
	LFE(s)	$4.10 \times 10^{0} \pm 2.9\%$	$2.04 \times 10^{2} \pm 2.9\%$	$4.65 \times 10^{1} \pm 2.4\%$
14.02	Rockwell	---	<2,000	<300
14.63	Rockwell	---	<2,000	<300
15.24	Rockwell	---	<2,000	<300
	LFE(s)	$1.67 \times 10^{0} \pm 2.4\%$	$7.93 \times 10^{1} \pm 2.4\%$	$1.94 \times 10^{1} \pm 4.6\%$

TABLE C-9. Plutonium and Americium Activity in Well 299-W18-181 (Sheet 3 of 5).

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
15.85	Rockwell	---	<2,000	<300
	LFE(s)	$2.53 \times 10^{-1} \pm 4.4\%$	$1.35 \times 10^{1} \pm 2.2\%$	$4.81 \times 10^{0} \pm 3.3\%$
16.46	Rockwell	---	<2,000	<300
	LFE(s)	$2.1 \times 10^{-2} \pm 14.3\%$	$7.8 \times 10^{-1} \pm 2.6\%$	$6.9 \times 10^{-2} \pm 4.4\%$
16.76	Rockwell	---	<2,000	<300
	EIC	$2.80 \times 10^{-1} \pm 22.8\%$	$1.38 \times 10^{1} \pm 9.1\%$	$3.14 \times 10^{0} \pm 7.1\%$
17.37	Rockwell	---	<2,000	<300
18.29	Rockwell	---	<2,000	<300
18.90	Rockwell	---	<2,000	<300
19.51	Rockwell	---	<2,000	<300
	EIC	$1.05 \times 10^{-1} \pm 12.7 \times 10^{-1}$	$7.0 \times 10^{-2} \pm 9.97 \times 10^{-2}$	$4.16 \times 10^{-2} \pm 2.21 \times 10^{-2}$
	LFE(s)	$1.2 \times 10^{-2} \pm 16.7\%$	$1.58 \times 10^{-1} \pm 5.7\%$	$2.7 \times 10^{-2} \pm 7.4\%$
19.81	Rockwell	---	<2,000	<300
	EIC	$2.59 \times 10^{-2} \pm 2.60 \times 10^{-2}$	$2.84 \times 10^{-1} \pm 29.6\%$	$8.82 \times 10^{-3} \pm 1.97 \times 10^{-2}$
20.12	Rockwell	---	<2,000	<300
20.73	Rockwell	---	<2,000	<300
21.34	Rockwell	---	<2,000	<300
21.95	Rockwell	---	<2,000	<300
22.56	Rockwell	---	<2,000	<300
22.86	Rockwell	---	<2,000	<300
	EIC	$2.11 \times 10^{-2} \pm 2.11 \times 10^{-2}$	$5.63 \times 10^{-2} \pm 3.61 \times 10^{-2}$	$3.74 \times 10^{-2} \pm 3.74 \times 10^{-2}$
23.16	Rockwell	---	<2,000	<300
23.77	Rockwell	---	<2,000	<300
24.38	Rockwell	---	<2,000	<300
	EIC	$-1.89 \times 10^{-2} \pm 2.68 \times 10^{-2}$	$1.79 \times 10^{-1} \pm 6.34 \times 10^{-2}$	$9.49 \times 10^{-1} \pm 12.2\%$

TABLE C-9. Plutonium and Americium Activity in Well 299-W18-181 (Sheet 4 of 5).

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
24.99	Rockwell	---	<2,000	<300
25.60	Rockwell	---	<2,000	<300
25.91	Rockwell	---	<2,000	<300
	EIC	$-1.52 \times 10^{-2} \pm 1.86 \times 10^{-2}$	$-7.62 \times 10^{-3} \pm 7.64 \times 10^{-3}$	$3.20 \times 10^{-1} \pm 17.0\%$
26.21	Rockwell	---	<2,000	<300
26.82	Rockwell	---	<2,000	<300
27.43	Rockwell	---	<2,000	<300
	EIC	1.66×10^{-2}	$-8.28 \times 10^{-3} \pm 2.19 \times 10^{-2}$	$1.24 \times 10^{-2} \pm 1.75 \times 10^{-2}$
28.04	Rockwell	---	<2,000	<300
28.65	Rockwell	---	<2,000	<300
28.96	Rockwell	---	<2,000	<300
29.26	Rockwell	---	<2,000	<300
30.48	Rockwell	---	<2,000	<300
	EIC	$2.33 \times 10^{-2} \pm 1.17 \times 10^{-2}$	$5.24 \times 10^{-2} \pm 2.28 \times 10^{-2}$	$7.16 \times 10^{-3} \pm 2.58 \times 10^{-2}$
31.09	Rockwell	---	<2,000	<300
32.00	Rockwell	---	<2,000	<300
32.31	Rockwell	---	<2,000	<300
32.92	Rockwell	---	<2,000	<300
	EIC	$1.23 \times 10^{-2} \pm 2.75 \times 10^{-2}$	$2.71 \times 10^{-1} \pm 28.7\%$	$2.15 \times 10^{-1} \pm 2.67 \times 10^{-1}$
33.53	Rockwell	---	<2,000	<300
	EIC	$1.79 \times 10^{-2} \pm 2.27 \times 10^{-2}$	$4.50 \times 10^{-2} \pm 4.87 \times 10^{-2}$	$4.64 \times 10^{-2} \pm 4.65 \times 10^{-2}$
34.14	Rockwell	---	<2,000	<300
34.75	Rockwell	---	<2,000	<300
35.05	Rockwell	---	<2,000	<300

TABLE C-9. Plutonium and Americium Activity in Well 299-W18-181 (Sheet 5 of 5).

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
35.36	Rockwell	---	<2,000	<300
35.97	Rockwell	---	<2,000	<300
36.58	Rockwell	---	<2,000	<300
	EIC	$1.80 \times 10^{-1} \pm 21\%$	$9.92 \times 10^{0} \pm 7.2\%$	$1.19 \times 10^{0} \pm 11.5\%$
37.19	Rockwell	---	<2,000	<300
37.80	Rockwell	---	<2,000	<300
38.10	Rockwell	---	<2,000	<300
38.40	Rockwell	---	<2,000	<300
	LFE(s)	$3.58 \times 10^{-1} \pm 4.8\%$	$1.87 \times 10^{+1} \pm 2.7\%$	$4.81 \times 10^{0} \pm 4.0\%$
	EIC	$2.25 \times 10^{-1} \pm 9.2 \times 10^{-2}$	$1.46 \times 10^{+1} \pm 11.0\%$	$2.89 \times 10^{0} \pm 8.8\%$
39.01	Rockwell	---	<2,000	<300
	LFE(s)	$7.6 \times 10^{-2} \pm 7.9\%$	$2.93 \times 10^{0} \pm 2.7\%$	$6.3 \times 10^{-1} \pm 4.8\%$
	EIC	$6.44 \times 10^{-2} \pm 3.41 \times 10^{-2}$	$4.10 \times 10^{0} \pm 8.8\%$	$4.91 \times 10^{-1} \pm 12\%$
39.62	Rockwell	---	<2,000	<300
	LFE	$5.2 \times 10^{-2} \pm 7.7\%$	$2.44 \times 10^{0} \pm 2.5\%$	$5.2 \times 10^{-1} \pm 3.8\%$
	LFE	$4.9 \times 10^{-2} \pm 10.2\%$	$2.49 \times 10^{0} \pm 2.81\%$	$5.0 \times 10^{-1} \pm 4.0\%$
	LFE	$4.4 \times 10^{-2} \pm 11.4\%$	$2.68 \times 10^{0} \pm 3.0\%$	$5.27 \times 10^{-1} \pm 2.7\%$
40.23	Rockwell	---	<2,000	<300
40.84	Rockwell	---	<2,000	<300
41.15	Rockwell	---	<2,000	<300
41.45	Rockwell	---	<2,000	<300
41.91	Rockwell	---	<2,000	<300
	LFE(s)	$1.29 \times 10^{-2} \pm 3.9\%$	$5.38 \times 10^{1} \pm 2.8\%$	$1.93 \times 10^{1} \pm 13.6\%$
	EIC	$9.52 \times 10^{-2} \pm 3.62 \times 10^{-2}$	$5.64 \times 10^{0} \pm 8.2\%$	$1.06 \times 10^{-1} \pm 9.98 \times 10^{-2}$

TABLE C-10. Plutonium and Americium Activity in Well 299-W18-182 (Sheet 1 of 2).

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
1.52	LFE	$0 \pm 1.3 \times 10^{-3}$	$2.05 \times 10^{-1} \pm 4.4\%$	$1.3 \times 10^{-2} \pm 15.4\%$
3.05	LFE	$-7.0 \times 10^{-4} \pm 1.3 \times 10^{-3}$	$1.4 \times 10^{-2} \pm 14.3\%$	$1.8 \times 10^{-2} \pm 16.7\%$
4.57	LFE	$3.2 \times 10^{-3} \pm 1.8 \times 10^{-3}$	$7.5 \times 10^{-2} \pm 6.7\%$	$1.9 \times 10^{-2} \pm 10.5\%$
6.17	Rockwell	---	$2.08 \times 10^{+6} \pm 25\%$	$1.64 \times 10^{+6} \pm 5\%$
	Rockwell	---	$1.84 \times 10^{+6} \pm 25\%$	$1.66 \times 10^{+6} \pm 5\%$
	Rockwell	---	$1.74 \times 10^{+6} \pm 25\%$	$1.64 \times 10^{+6} \pm 5\%$
6.50	Rockwell	---	$1.39 \times 10^{+6} \pm 5\%$	$4.30 \times 10^{+5} \pm 15\%$
	Rockwell	---	$1.34 \times 10^{+6} \pm 5\%$	$4.11 \times 10^{+5} \pm 15\%$
6.84	Rockwell	---	$1.01 \times 10^{+5} \pm 25\%$	$1.44 \times 10^{5} \pm 20\%$
	Rockwell	---	$1.06 \times 10^{+5} \pm 30\%$	$1.36 \times 10^{5} \pm 20\%$
7.5	Rockwell	---	<2,000	$1.02 \times 10^{3} \pm 25\%$
	Rockwell	---	$3.3 \times 10^{3} \pm 30\%$	$6.6 \times 10^{2} \pm 30\%$
8.17	Rockwell	---	<2,000	<200
	Rockwell	---	<2,000	<200
	Rockwell	---	<2,000	<200
8.84	Rockwell	---	<2,000	<300
	LFE	$4.2 \times 10^{-1} \pm 7.1\%$	$2.71 \times 10^{0} \pm 3.3\%$	$3.6 \times 10^{0} \pm 5.6\%$
	EIC	$4.04 \times 10^{0} \pm 8.9\%$	$3.05 \times 10^{+1} \pm 7.8\%$	$2.52 \times 10^{+1} \pm 6.6\%$
10.36	Rockwell	---	<2,000	<300
10.67	Rockwell	---	<2,000	<300
	LFE(s)	$1.3 \times 10^{-2} \pm 23.1\%$	$3.78 \times 10^{-1} \pm 3.4\%$	$1.01 \times 10^{-1} \pm 3.0\%$
	EIC	$-2.26 \times 10^{-2} \pm 3.20 \times 10^{-2}$	$1.36 \times 10^{-1} \pm 32.4\%$	$6.69 \times 10^{0} \pm 7.6\%$
10.97	Rockwell	---	<2,000	<300
11.28	Rockwell	---	<2,000	<300
	EIC	$1.02 \times 10^{0} \pm 10.4\%$	$3.93 \times 10^{0} \pm 7.7\%$	$1.59 \times 10^{+1} \pm 6.2\%$
11.89	Rockwell	---	<2,000	<300

TABLE C-10. Plutonium and Americium Activity in Well 299-W18-182 (Sheet 2 of 2).

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
12.19	Rockwell	---	<2,000	<300
	LFE(s)	$3.7 \times 10^{-3} \pm 1.5 \times 10^{-3}$	$1.18 \times 10^{-1} \pm 5.1\%$	$3.14 \times 10^{0} \pm 3.5\%$
	EIC	$1.39 \times 10^{-2} \pm 9.8 \times 10^{-3}$	$2.09 \times 10^{-2} \pm 2.09 \times 10^{-2}$	$4.19 \times 10^{0} \pm 5.2\%$
12.50	Rockwell	---	<2,000	<300

TABLE C-11. Plutonium and Americium Activity in Well 299-W18-183 (Sheet 1 of 2).

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
1.83	Rockwell	---	<2,000	<300
2.44	Rockwell	---	<2,000	<300
3.05	Rockwell	---	<2,000	<300
3.66	Rockwell	---	<2,000	<300
4.27	Rockwell	---	<2,000	<300
4.57	Rockwell	---	<2,000	<300
	EIC	$3.70 \times 10^{-2} \pm 1.98 \times 10^{-2}$	$4.67 \times 10^{-1} \pm 15\%$	$2.95 \times 10^{-2} \pm 1.12 \times 10^{-2}$
4.88	Rockwell	---	<2,000	<300
	EIC	$7.40 \times 10^{-3} \pm 2.2 \times 10^{-2}$	$2.22 \times 10^{-2} \pm 2.46 \times 10^{-2}$	$5.72 \times 10^{-2} \pm 2.90 \times 10^{-2}$
5.79	Rockwell	---	<2,000	<300
	EIC	$5.59 \times 10^{-2} \pm 28.8\%$	$4.86 \times 10^{-1} \pm 8.2\%$	$1.12 \times 10^{-1} \pm 28.3\%$
6.10	Rockwell	---	<2,000	<300
	EIC	$1.27 \times 10^{-2} \pm 1.27 \times 10^{-2}$	$1.07 \times 10^{-1} \pm 20.6\%$	$4.64 \times 10^{-2} \pm 2.82 \times 10^{-2}$
6.40	Rockwell	---	<2,000	<300
6.86	Rockwell	---	<2,000	<300
	LFE(s)	$1.02 \times 10^{-2} \pm 15.7\%$	$1.43 \times 10^{-1} \pm 3.5\%$	$2.5 \times 10^{-2} \pm 12.0\%$
	EIC	$3.66 \times 10^{-2} \pm 29.2\%$	$5.49 \times 10^{-2} \pm 2.13 \times 10^{-2}$	$3.92 \times 10^{-3} \pm 2.4 \times 10^{-2}$
7.32	Rockwell	---	<2,000	<300
7.62	Rockwell	---	<2,000	<300
	EIC	$9.99 \times 10^{-1} \pm 6.6\%$	$8.29 \times 10^{0} \pm 4.5\%$	$1.30 \times 10^{0} \pm 12.0\%$
7.92	Rockwell	---	<2,000	<300
8.53	Rockwell	---	<2,000	<300
9.14	LFE	$2.2 \times 10^{-2} \pm 13.6\%$	$9.8 \times 10^{-2} \pm 7.1\%$	$1.08 \times 10^{-1} \pm 7.41\%$
	EIC	$3.83 \times 10^{-2} \pm 29.4\%$	$1.68 \times 10^{-1} \pm 15.4\%$	$1.60 \times 10^{-1} \pm 5.8 \times 10^{-2}$

TABLE C-11. Plutonium and Americium Activity in Well 299-W18-183 (Sheet 2 of 2).

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
9.75	Rockwell	---	<2,000	<300
10.36	Rockwell	---	<2,000	<300
10.67	Rockwell	---	<2,000	<300
	EIC	$3.25 \times 10^{-2} \pm 32\%$	$1.02 \times 10^{-1} \pm 19.5\%$	$1.74 \times 10^{-1} \pm 24.4\%$
10.97	Rockwell	---	<2,000	<300
	EIC	$-1.58 \times 10^{-2} \pm 2.42 \times 10^{-2}$	$8.98 \times 10^{-2} \pm 27.6\%$	$6.56 \times 10^{-2} \pm 3.9 \times 10^{-2}$
11.89	Rockwell	---	<2,000	<300
	EIC	$1.64 \times 10^{-2} \pm 1.40 \times 10^{-2}$	$1.99 \times 10^{-1} \pm 12.8\%$	$7.60 \times 10^{-2} \pm 4.96 \times 10^{-2}$
12.50	Rockwell	---	<2,000	<300
	LFE(s)	$4 \times 10^{-3} \pm 2 \times 10^{-3}$	$2.92 \times 10^{-1} \pm 4.1\%$	$7.70 \times 10^{-2} \pm 6.5\%$
	EIC	$1.68 \times 10^{-2} \pm 2.06 \times 10^{-2}$	$2.08 \times 10^{-1} \pm 24.8\%$	$3.82 \times 10^{-2} \pm 4.28 \times 10^{-2}$

TABLE C-12. Plutonium and Americium Activity in Well 299-W18-184.

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
5.64	LFE	$3.9 \times 10^{-2} \pm 10\%$	$8.7 \times 10^{-1} \pm 2.3\%$	$4.4 \times 10^{-1} \pm 3.41\%$
	EIC	$9.04 \times 10^{-2} \pm 3.42 \times 10^{-2}$	$9.85 \times 10^{-1} \pm 13.7\%$	$6.06 \times 10^{-1} \pm 16.3\%$
6.44	Rockwell	---	$3.00 \times 10^{3}_{4} \pm 30\%$	$8.80 \times 10^{3}_{3} \pm 20\%$
	Rockwell	---	$1.56 \times 10^{4} \pm 25\%$	$8.56 \times 10^{3} \pm 20\%$
	Rockwell	---	$1.87 \times 10^{4} \pm 25\%$	$8.69 \times 10^{3} \pm 20\%$
6.85	Rockwell	---	$1.61 \times 10^{5}_{5} \pm 8\%$	$1.22 \times 10^{5}_{5} \pm 20\%$
	Rockwell	---	$1.82 \times 10^{5} \pm 15\%$	$1.20 \times 10^{5} \pm 20\%$
7.26	Rockwell	---	<2,000	<200
	Rockwell	---	<2,000	<200
7.67	Rockwell	---	<2,000	<200
	Rockwell	---	<2,000	<200
	Rockwell	---	<2,000	<200
9.75	LFE	$5.0 \times 10^{-3} \pm 3.0 \times 10^{-3}$	$1.88 \times 10^{-1} \pm 6.4\%$	$6.8 \times 10^{-1} \pm 4.40\%$
	LFE	$4.3 \times 10^{-3} \pm 1.9 \times 10^{-3}$	$1.38 \times 10^{-1} \pm 5.8\%$	$5.3 \times 10^{-1} \pm 3.8\%$
	LFE	$4.0 \times 10^{-3} \pm 2.0 \times 10^{-3}$	$1.43 \times 10^{-1} \pm 5.6\%$	$5.9 \times 10^{-1} \pm 8.5\%$
	EIC	$2.83 \times 10^{-2} \pm 2.12 \times 10^{-3}$	$1.51 \times 10^{-1} \pm 29.2\%$	$6.76 \times 10^{-1} \pm 12.4\%$
	EIC	$-7.63 \times 10^{-3} \pm 7.65 \times 10^{-3}$	$4.66 \times 10^{-2} \pm 5.28 \times 10^{-2}$	$4.58 \times 10^{-1} \pm 15.7\%$
	EIC	$2.27 \times 10^{-2} \pm 1.32 \times 10^{-3}$	$1.52 \times 10^{-1} \pm 29.2\%$	$4.47 \times 10^{-1} \pm 17.8\%$
10.36	LFE(s)	$1.25 \times 10^{-2} \pm 25\%$	$4.33 \times 10^{-1} \pm 4.2\%$	$1.03 \times 10^{0}_{1} \pm 3.9\%$
	EIC	$4.67 \times 10^{-2} \pm 1.05 \times 10^{-1}$	$1.40 \times 10^{-1} \pm 2.25 \times 10^{-1}$	$3.55 \times 10^{-1} \pm 18.1\%$
10.67	LFE(s)	$9.0 \times 10^{-3} \pm 22\%$	$3.64 \times 10^{-1} \pm 4.1\%$	$6.8 \times 10^{-1} \pm 2.9\%$
	EIC	$2.13 \times 10^{-2} \pm 1.88 \times 10^{-2}$	$1.21 \times 10^{-1} \pm 25.2\%$	$1.33 \times 10^{0} \pm 11.1\%$

TABLE C-13. Plutonium and Americium Activity in Well 299-W18-185.

Depth (m)	Laboratory	^{238}Pu (pCi/g)	$^{239,240}Pu$ (pCi/g)	^{241}Am (pCi/g)
5.59	EIC	$2.95 \times 10^{-2} \pm 1.96 \times 10^{-2}$	$1.89 \times 10^{-1} \pm 21.2\%$	$2.92 \times 10^{-1} \pm 21.4\%$
5.81	Rockwell	---	$1.75 \times 10^{+6} \pm 25\%$	$3.64 \times 10^{5} \pm 15\%$
6.0	Rockwell	---	$3.08 \times 10^{6} \pm 5\%$	$8.63 \times 10^{5} \pm 10\%$
6.19	Rockwell	---	$2.20 \times 10^{6} \pm 5\%$	$8.74 \times 10^{5} \pm 10\%$
	Rockwell	---	$2.11 \times 10^{6} \pm 8\%$	$7.44 \times 10^{5} \pm 10\%$
6.57	Rockwell	---	$1.38 \times 10^{6} \pm 18\%$	$6.09 \times 10^{5} \pm 10\%$
	Rockwell	---	$1.16 \times 10^{6} \pm 5\%$	$6.04 \times 10^{5} \pm 10\%$
	Rockwell	---	$1.06 \times 10^{6} \pm 20\%$	$6.50 \times 10^{5} \pm 10\%$
6.95	Rockwell	---	$2.22 \times 10^{5} \pm 5\%$	$1.07 \times 10^{5} \pm 20\%$
	Rockwell	---	$2.42 \times 10^{5} \pm 21\%$	$1.03 \times 10^{5} \pm 20\%$
7.70	Rockwell	---	<2,000	<200
	Rockwell	---	<2,000	<200
	Rockwell	---	<2,000	<200
8.69	LFE	$2.0 \times 10^{-2} \pm 20\%$	$1.07 \times 10^{0} \pm 3.7\%$	$4.95 \times 10^{0} \pm 2.0\%$
	LFE	$2.6 \times 10^{-2} \pm 11.5\%$	$1.25 \times 10^{0} \pm 2.4\%$	$4.13 \times 10^{0} \pm 2.4\%$
	EIC	$9.34 \times 10^{-2} \pm 3.83 \times 10^{-2}$	$1.16 \times 10^{0} \pm 13.2\%$	$3.59 \times 10^{0} \pm 8.7\%$
9.75	EIC	$3.26 \times 10^{-2} \pm 3.93 \times 10^{-2}$	$4.45 \times 10^{-1} \pm 18.4\%$	$2.13 \times 10^{-1} \pm 30.1\%$
10.36	EIC	$1.57 \times 10^{-2} \pm 1.57 \times 10^{-2}$	$4.86 \times 10^{-1} \pm 16.1\%$	$4.66 \times 10^{-1} \pm 29.3\%$
10.67	EIC	$2.60 \times 10^{-2} \pm 3.98 \times 10^{-2}$	$8.83 \times 10^{-1} \pm 12.8\%$	$6.61 \times 10^{-1} \pm 16.4\%$
12.19	LFE(s)	$1.7 \times 10^{-2} \pm 7 \times 10^{-3}$	$1.15 \times 10^{0} \pm 2.6\%$	$1.59 \times 10^{-1} \pm 4.4\%$
	EIC	$4.99 \times 10^{-1} \pm 16.5\%$	$1.90 \times 10^{+1} \pm 8.6\%$	$7.47 \times 10^{0} \pm 8.8\%$
	LFE(s)	$9.4 \times 10^{-1} \pm 3.2\%$	$4.05 \times 10^{+1} \pm 2.5\%$	$1.63 \times 10^{+1} \pm 2.4\%$
12.80	EIC	$2.93 \times 10^{-2} \pm 5.87 \times 10^{-2}$	$3.32 \times 10^{0} \pm 11.9\%$	$1.38 \times 10^{0} \pm 11.8\%$

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APPENDIX D

PASSIVE NEUTRON FLUX MEASUREMENTS[a]

Depth (m)	Counts/2 min
Well 299-W18-154	
3.0	0
3.25	0
3.5	0
3.75	1
4.0	1
4.25	3
4.5	6
4.75	21
5.0	46
5.25	37
5.5	8
5.75	8
6.0	2
Well 299-W18-162	
5.5	2,088
5.75	7,166
5.9	10,663
6.0	10,383
6.13	6,754
6.25	4,210
6.50	954
6.75	209
7.00	42
7.25	13
8.00	1
8.25	3
8.50	1
Well 299-W18-179	
3.0	1
4.0	9
4.5	53
4.75	171
4.8	226
4.9	366
5.0	476
5.1	513
5.2	560
5.3	563

Depth (m)	Counts/2 min
Well 299-W18-179 (cont'd)	
5.4	399
5.5	233
5.6	157
5.7	80
6.0	12
6.5	5
7.0	1
8.0	1
9.0	1
Well 299-W18-180	
4.5	2
5.0	1
5.5	1
6.0	1
6.5	0
7.0	2
7.5	2
8.0	0
8.5	1
9.0	1
Well 299-W18-181	
4.5	8
5.0	36
5.25	136
5.4	265
5.5	284
5.6	419
5.7	658
5.8	1,000
5.9	1,444
6.0	1,932
6.1	2,334
6.2	2,335
6.3	1,881
6.4	1,485
6.5	1,061
6.6	650
6.7	415

Depth (m)	Counts/2 min
Well 299-W18-181 (cont'd)	
6.8	262
6.9	157
7.0	93
7.5	24
8.0	16
9.0	12
Well 299-W18-182	
4.5	4
5.0	16
5.5	61
5.6	122
5.7	155
5.8	277
5.9	332
6.0	508
6.1	735
6.2	854
6.3	920.
6.4	826
6.5	762
6.6	585
6.7	407
6.8	288
6.9	155
7.0	50
7.5	7
8.0	1
9.0	0
Well 299-W18-183	
4.5	0
5.5	0
6.0	0
6.5	0
7.0	0
7.5	0
8.0	0
9.0	0
Well 299-W18-184	
4.5	6
5.0	5
5.5	7
6.0	15
6.5	27
6.75	39
7.0	37
7.25	6
7.50	8
8.0	4
8.5	3
9.0	2
Well 299-W18-185	
4.5	6
5.0	12
5.25	49
5.5	148
5.6	249
5.7	315
5.8	410
5.9	461
6.0	466
6.1	381
6.2	327
6.3	255
6.4	234
6.5	203
6.6	170
6.7	160
6.8	125
6.9	76
7.0	55
7.5	8
8.0	2
9.0	1

[a]All measurements were performed using a Campbell Pacific Nuclear Model 503 1.5-in.-diam "depth probe" without neutron source.

APPENDIX E

MOISTURE CONTENT OF SEDIMENT SAMPLES

Depth (m)	Moisture Content (wt%)
Well 299-W18-179	
0.61	4.68
1.22	4.95
1.52	6.18
1.83	5.54
2.44	5.45
3.05	2.92
3.66	3.22
4.27	3.27
4.57	3.47
4.88	4.41
6.71	12.38
7.32	3.59
7.62	3.68
7.92	4.61
8.53	3.97
9.14	3.85
9.75	3.90
10.36	5.86
10.67	8.49
10.97	3.16
11.58	3.20
12.19	3.40
12.80	3.63
Well 299-W18-180	
5.79	7.39
6.10	3.46
7.01	3.75
9.14	9.67
9.75	3.26
10.67	3.65
12.19	3.56
Well 299-W18-181	
0.61	5.18
1.22	5.21
2.13	6.35
2.74	5.63
3.05	8.40
3.66	4.79
4.27	6.77
4.57	5.88
5.87	10.10
6.25	9.04
7.36	2.68
8.11	3.10
14.63	2.98
15.24	5.13
15.85	6.80
16.46	12.72
16.76	8.48
17.37	14.39
18.29	4.16
18.90	8.57
19.51	13.87
19.81	4.00
20.12	3.92
20.73	4.67
21.34	5.41
21.95	6.39
22.56	5.84
22.86	5.30
23.16	3.98
23.77	10.68
24.38	13.26
24.99	3.44
25.60	5.19
25.91	10.71
26.21	4.58
26.82	11.57
27.43	3.64
28.04	3.36
28.65	5.07
28.96	3.73
29.26	3.33
29.87	2.95
30.48	3.39
31.09	3.31
31.70	3.77
32.00	5.15

Depth (m)	Moisture Content (wt%)
Well 299-W18-181 (cont'd)	
32.31	5.50
32.92	12.76
33.53	3.07
34.14	3.16
34.75	2.85
35.05	3.18
35.36	3.13
35.97	3.22
36.58	3.33
37.19	2.73
37.80	2.55
38.10	2.86
38.40	3.47
39.01	17.81
39.62	13.95
40.23	19.72
40.84	12.42
41.15	18.80
41.45	13.17
41.91	7.09
Well 299-W18-182	
0.61	3.96
1.22	5.34
1.52	4.25
1.83	5.45
2.44	6.46
3.05	6.41
3.66	6.51
4.27	6.62
4.57	7.29
4.88	8.76
6.17	9.06
6.50	3.79
6.84	3.32
7.5	8.42
8.17	4.13
8.84	15.66
10.36	3.79
10.67	3.09
10.97	3.93
11.89	4.13
12.19	5.91
12.50	11.90

Depth (m)	Moisture Content (wt%)
Well 299-W18-183	
0.61	4.70
1.52	5.15
1.83	4.46
2.34	4.63
3.05	2.52
3.66	3.06
4.29	3.59
4.57	2.37
4.88	2.43
5.79	2.14
6.10	1.90
6.40	1.87
6.86	2.71
7.32	3.26
7.92	3.05
8.53	3.47
9.14	4.60
9.75	7.98
10.36	5.40
10.67	3.58
10.97	4.80
11.89	3.47
12.50	3.56
Well 299-W18-184	
0.61	5.56
1.22	6.20
1.52	5.26
1.83	5.48
2.44	5.15
3.05	6.51
3.66	8.02
4.27	7.58
4.57	5.88
4.88	5.76
5.64	5.15
6.03	2.69
6.44	4.64
6.85	8.46
7.26	3.16
7.67	2.55
9.75	5.39
10.36	3.82
10.67	3.34

Depth (m)	Moisture Content (wt%)	Depth (m)	Moisture Content (wt%)
Well 299-W18-185		Well 299-W18-185 (cont'd)	
0.61	4.53	6.57	4.75
1.22	4.56	6.95	7.49
1.52	4.60	7.70	2.72
1.83	6.16	8.69	12.15
2.44	3.56	9.75	3.83
3.05	2.39	10.36	3.22
3.66	2.95	10.67	3.13
4.27	4.47	10.97	3.14
4.57	3.60	11.58	3.50
4.88	5.67	12.19	3.79
5.33	4.41	12.80	3.40
6.19	12.18		

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APPENDIX F

NEUTRON LOGGING MEASUREMENTS

Passive neutron logging was used primarily as an aid in sectioning the inner tube of the dual-wall core-barrel. Characteristics of the system discussed previously limited the value of the technique in quantitative determination of transuranic concentrations. However, the data provide useful qualitative information on the distribution of transuranic activity, which can supplement the laboratory data discussed in the text. The data also aid in visualization of the transuranic distribution.

Passive neutron logging was performed for all wells drilled during the current study (154, 179 through 185) and Well 162. Results are reported in Appendix D. Neutron flux measurements above background (0 to 2 counts/2 min) were not detected in Wells 180 or 183. In the remaining wells, the neutron flux (in counts/2 min) were plotted versus depth in Figures F-1 through F-7. Plutonium and americium activity were also plotted for comparison. Laboratory determined plutonium and americium activity were plotted in nanocuries per gram to permit the display of both data sets using the same scale. The laboratory results are discussed in detail in the text and are only briefly covered here.

Wells 162, 181, 182, and 185 (see Figures F-2, F-4, F-5, and F-7) all penetrated the crib bottom and encountered contaminated sediment. Peak transuranic activity occurred in all cases at a depth of approximately 6 m (20 ft), the depth of the crib bottom. The general pattern defined by the neutron flux measurements and transuranic activity data were similar, but not identical. The shape of the curve defined by neutron flux measurements were in all cases broader than the transuranic activity-defined curve. This pattern is typical of logging systems, which generally average the measurement over a much larger volume than represented by the laboratory sample. Both data sets indicated the highest transuranic activity was present in a very narrow zone located at or immediately below the crib bottom. Transuranic activity decreased rapidly with depth.

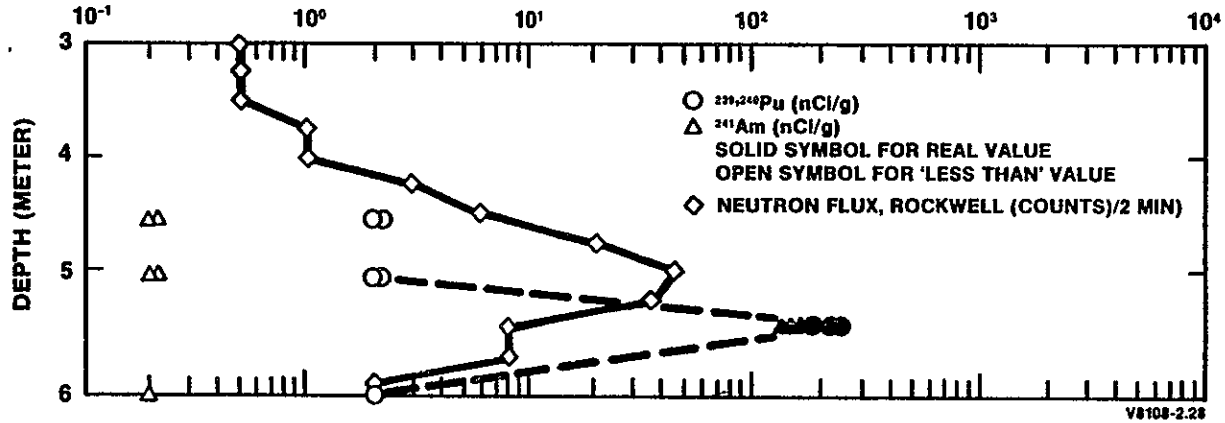

FIGURE F-1. Plot of Neutron Log and Transuranic Activity Data for Well 299-W18-154.

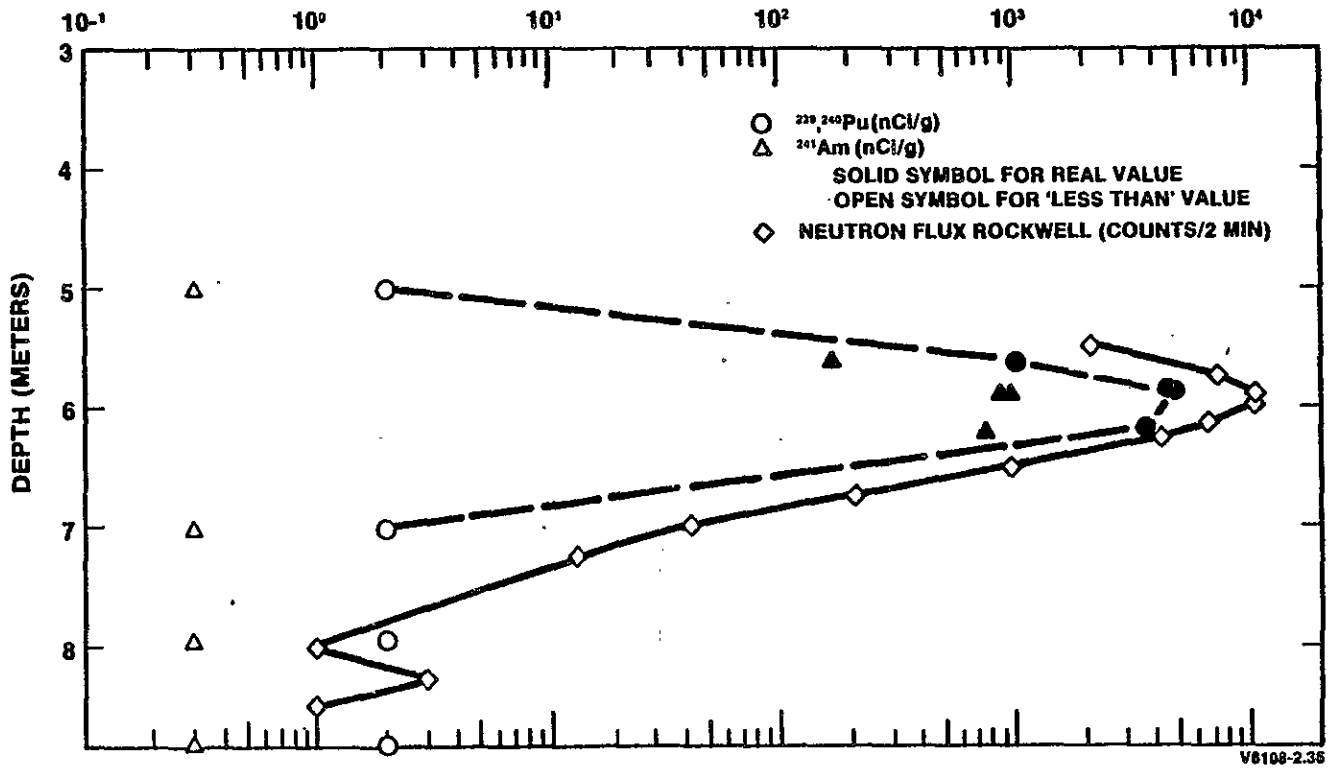

FIGURE F-2. Plot of Neutron Log and Transuranic Activity Data for Well 299-W18-162.

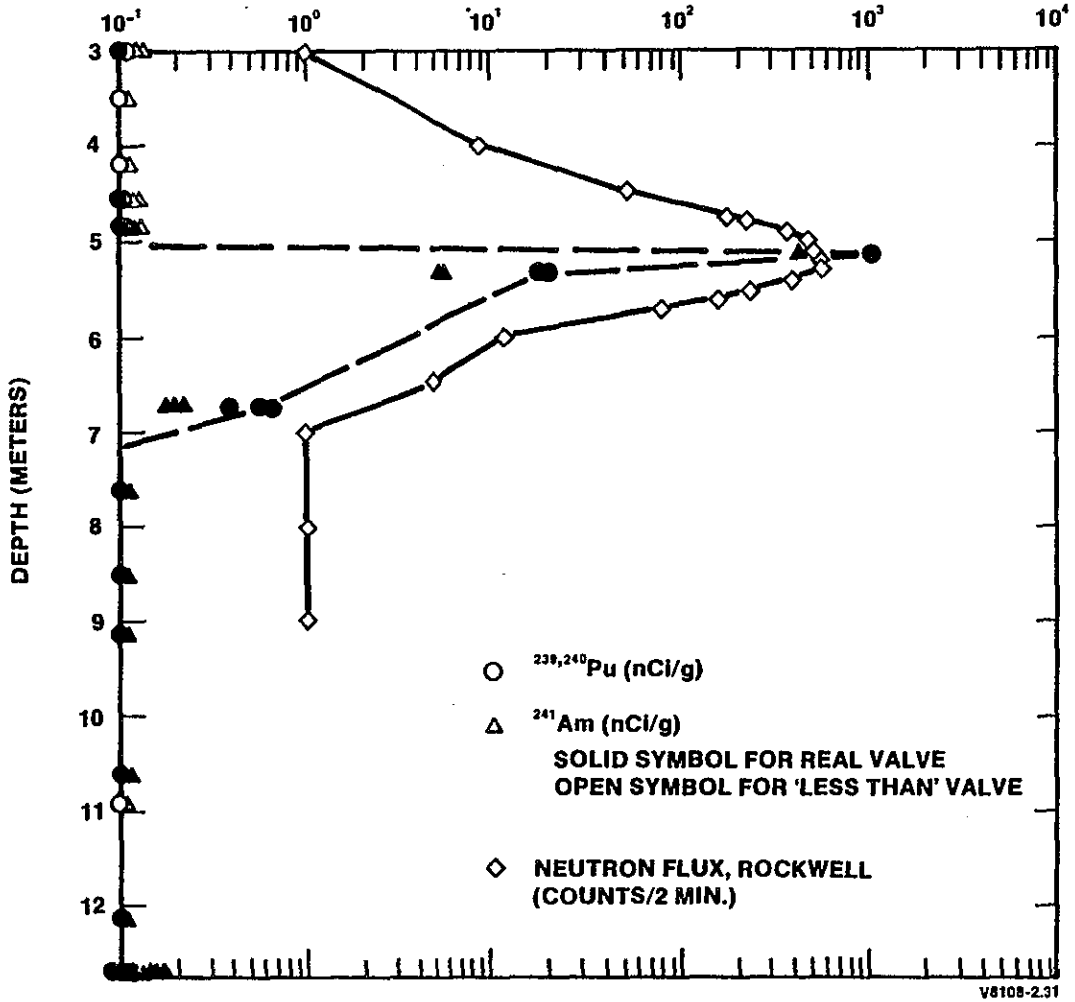

FIGURE F-3. Plot of Neutron Log and Transuranic Activity Data for Well 299-W18-179.

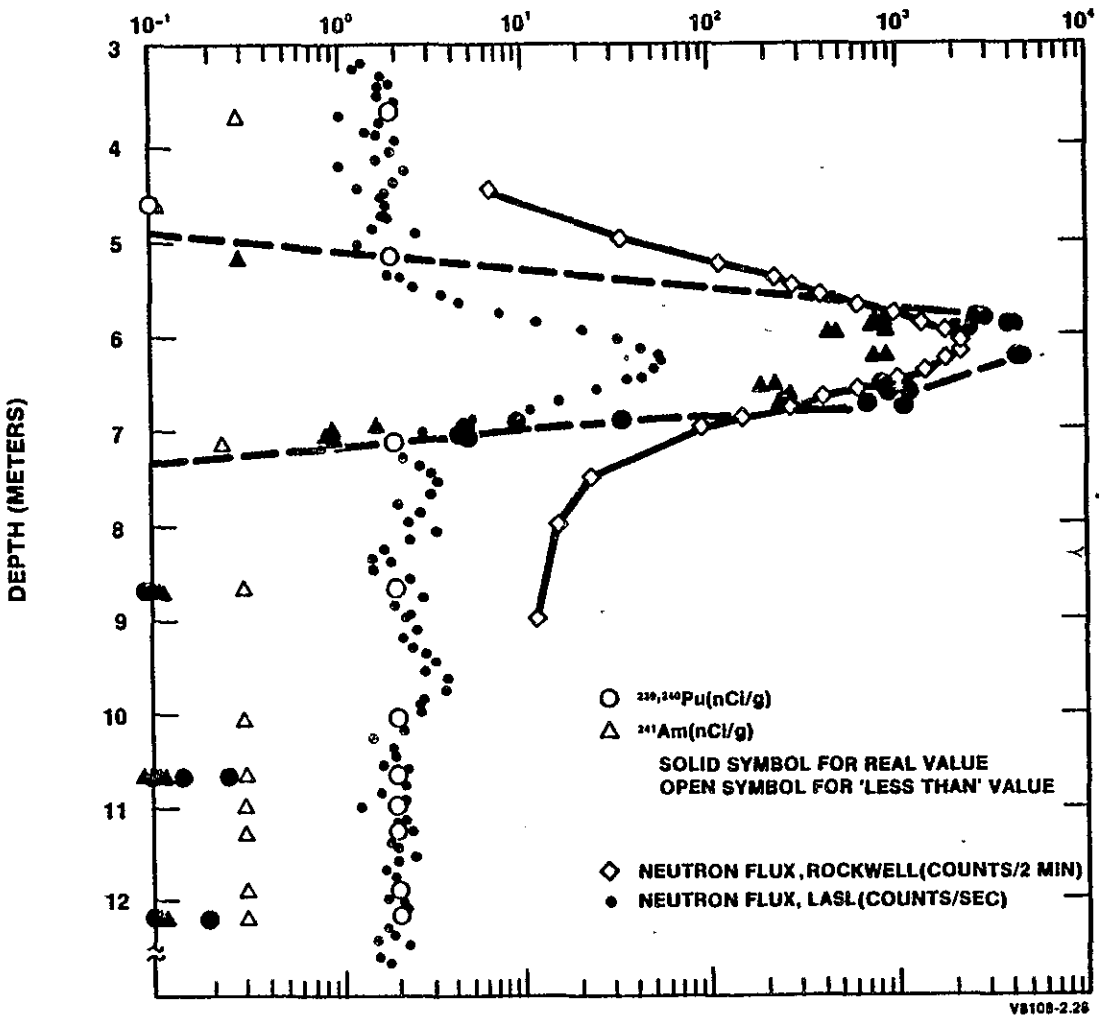

FIGURE F-4. Plot of Neutron Log and Transuranic Activity Data for Well 299-W18-181.

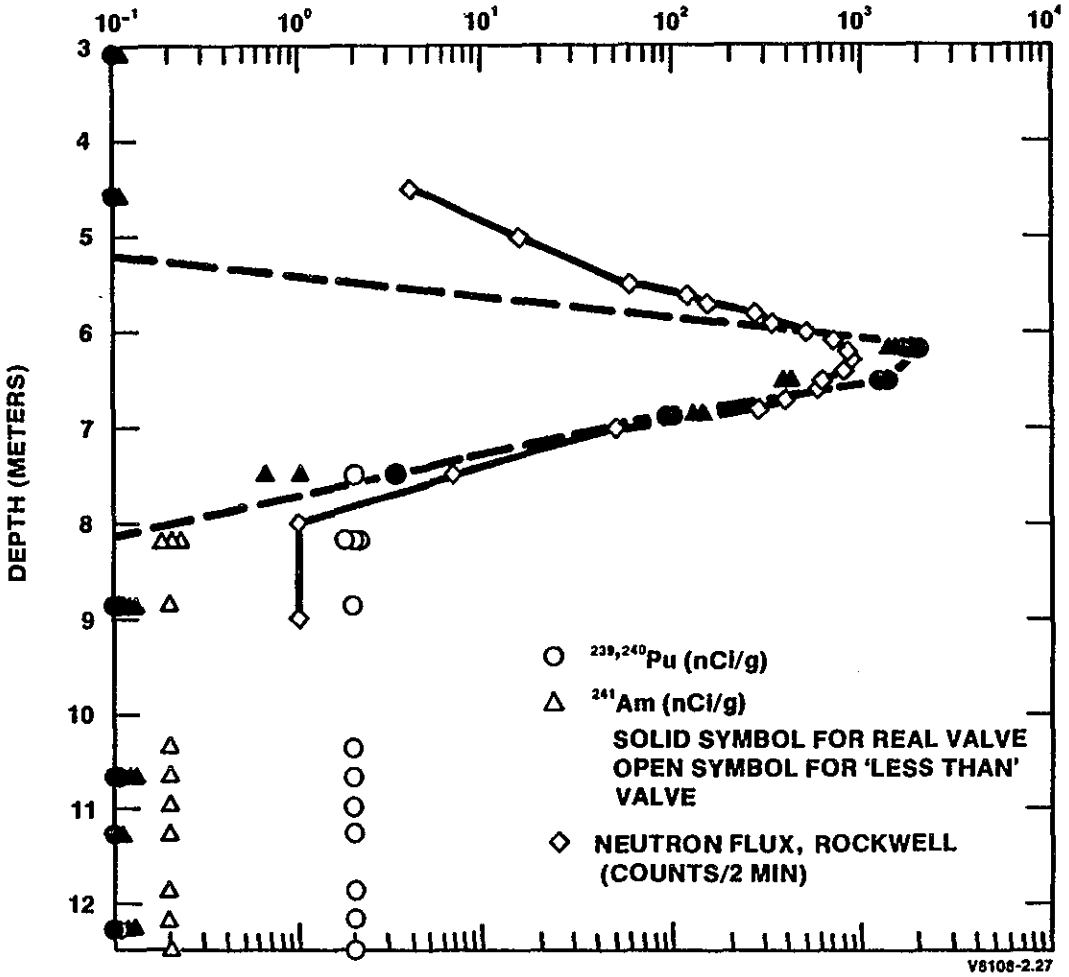

FIGURE F-5. Plot of Neutron Log and Transuranic Activity Data for Well 299-W18-182.

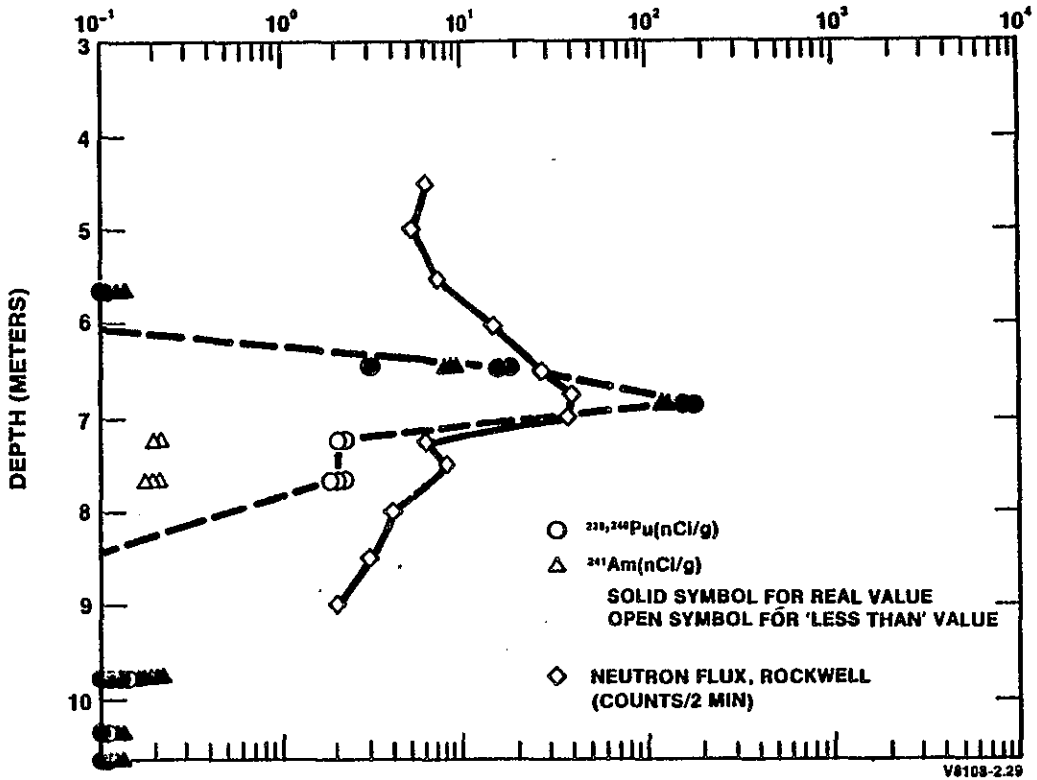

FIGURE F-6. Plot of Neutron Log and Transuranic Activity Data for Well 299-W18-184.

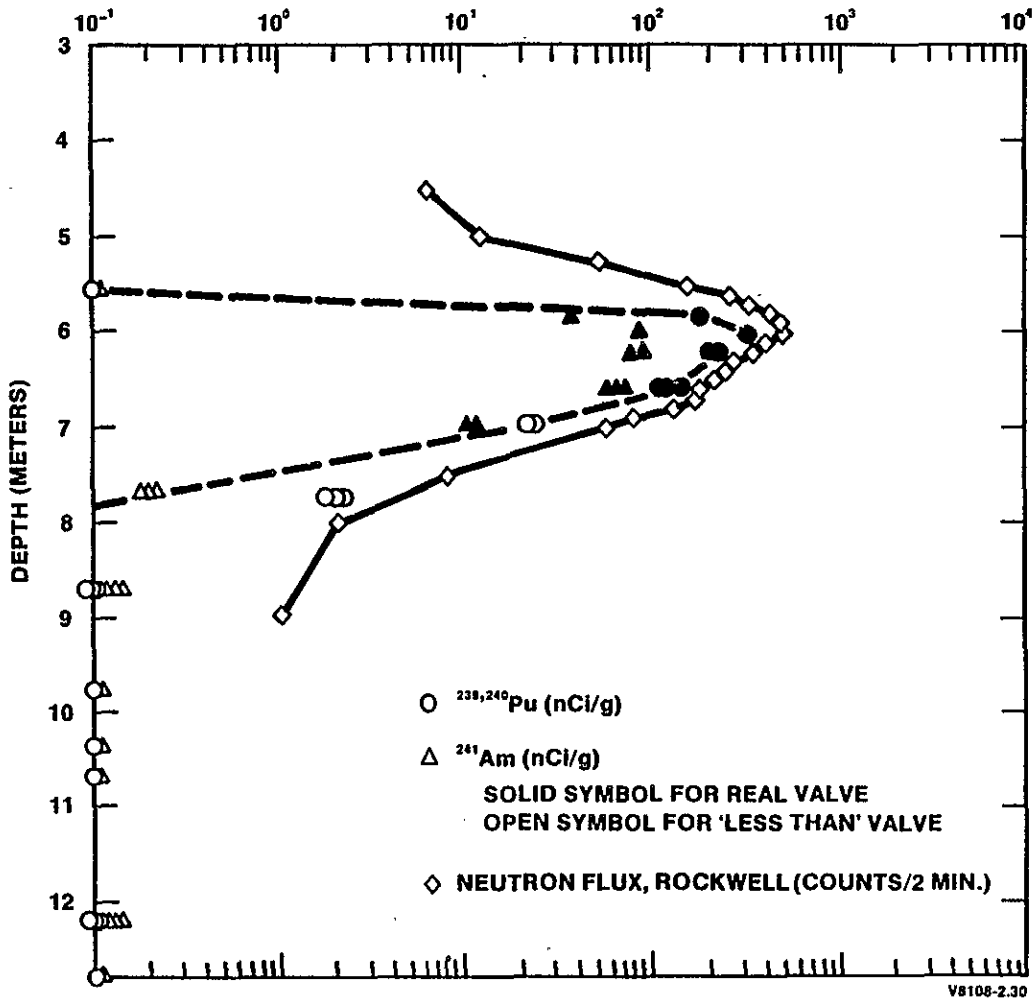

FIGURE F-7. Plot of Neutron Log and Transuranic Activity Data for Well 299-W18-185.

In addition to the passive neutron logging, the results from Table F-1 using the active system developed by Los Alamos for the Well 181 logging are also plotted in Figure F-4 for comparison. The neutron flux measurements for the Los Alamos system represented primarily the prompt fission neutrons from induced fissioning of plutonium. The peak defined by the Los Alamos data was narrower than that defined by the passive neutron logging data. This was due primarily to the smaller volume of interrogation (~60 L) and better resolution of the Los Alamos system. Peak activity for the Los Alamos system appeared to be at a slightly greater depth than for the passive system. The difference was due to the different geometries of the two systems and was not a function of the distribution of transuranic activity. For the passive system, the highest neutron flux was measured when the detector was centered on the zone of highest activity. For the active system, the highest neutron flux was measured when the source of activity was centered between the neutron source and the detector. Since the Los Alamos system was tested without any modification, a correction was not made in the raw data presented in Table F-1, so the results as plotted were shifted approximately 0.2 m deeper relative to the passive logging results.

Results for logging Well 181 indicate the Los Alamos system shows promise. The system appears to be able to log plutonium activity with an acceptable representation of the distribution with depth. The small volume of interrogation results in significantly better resolution of plutonium distribution than provided by the passive system. However, without calibration of the system and evaluation of all the data collected during testing of the system at Hanford, it is not possible to determine if the system can currently meet the requirement of determining plutonium activity down to 10,000 pCi/g.

Wells 154 and 179 were located between the crib proper and the diversion box. Plots of the neutron flux measurements and transuranic activity are shown in Figures F-1 and F-3. Neutron flux measurements peaked at a depth of approximately 5 m (17 ft), 1 m higher than in the wells that penetrated the crib bottom. For Well 154, the neutron flux measurements did not correspond to the transuranic activity. Well 154

TABLE F-1. Active Neutron Logging Results for Well 181.*

Depth (m)	Counts / sec	Depth (m)	Counts / sec	Depth (m)	Counts / sec	Depth (m)	Counts / sec
15.54	1.57	11.91	1.78	8.13	2.39	4.26	2.32
15.47	1.78	11.85	1.84	8.07	3.28	4.20	1.02
15.44	2.12	11.73	1.84	7.95	2.39	4.11	1.64
15.38	1.78	11.66	1.71	7.85	2.73	4.04	1.98
15.32	1.71	11.57	1.98	7.76	2.05	3.95	2.05
15.23	1.50	11.51	2.39	7.64	3.07	3.89	1.64
15.14	1.78	11.42	1.98	7.55	3.35	3.83	1.43
15.08	2.12	11.36	1.78	7.46	3.01	3.77	1.71
14.99	1.78	11.27	2.39	7.37	2.66	3.68	1.02
14.90	1.91	11.18	1.98	7.28	2.25	3.62	1.64
14.80	2.12	11.12	2.19	7.15	1.84	3.53	2.05
14.71	1.64	10.99	1.23	7.09	2.60	3.47	1.71
14.62	1.78	10.93	2.12	7.00	2.80	3.37	1.71
14.54	1.64	10.81	1.64	6.88	5.12	3.34	1.91
14.47	1.30	10.75	2.19	6.79	11.14	3.25	1.71
14.38	1.50	10.66	1.98	6.70	16.60	3.19	1.23
14.29	1.98	10.57	2.25	6.57	25.82	3.10	1.37
14.19	1.57	10.51	1.64	6.48	36.55	3.04	2.05
14.10	2.32	10.42	1.91	6.42	44.82	2.95	1.23
14.01	1.64	10.35	1.98	6.36	50.90	2.89	1.78
13.95	1.50	10.23	1.43	6.27	56.50	2.83	1.30
13.86	2.32	10.17	2.12	6.21	53.63	2.73	1.37
13.77	1.84	10.08	1.98	6.12	44.68	2.64	1.84
13.71	1.57	9.99	2.66	6.03	33.41	2.55	1.64
13.62	1.91	9.90	2.60	5.93	21.66	2.43	1.57
13.52	1.91	9.81	2.73	5.84	12.30	2.37	1.16
13.43	2.12	9.74	3.55	5.75	7.51	2.28	1.30
13.37	2.12	9.62	3.69	5.66	4.30	2.22	1.43
13.25	2.19	9.53	2.80	5.57	3.69	2.12	1.64
13.19	2.32	9.44	3.14	5.48	2.60	2.06	1.37
13.10	2.60	9.35	2.87	5.39	2.19	1.97	1.57
13.01	2.53	9.29	2.46	5.32	1.84	1.91	1.64
12.91	2.87	9.17	2.12	5.20	1.98	1.82	1.43
12.82	1.98	9.10	2.60	5.14	1.43	1.73	1.23
12.73	2.19	8.98	2.25	5.02	1.30	1.64	1.16
12.64	1.78	8.92	2.39	4.93	2.66	1.55	1.50
12.58	1.57	8.83	1.98	4.87	1.57	1.45	1.50
12.49	2.25	8.74	2.73	4.78	1.98	1.36	1.37
12.40	1.50	8.65	2.12	4.72	1.71	1.27	1.16
12.34	1.84	8.56	2.39	4.62	1.84	1.21	1.37
12.24	1.71	8.46	1.50	4.56	1.71	1.12	1.30
12.15	2.05	8.37	1.91	4.50	1.84	1.03	1.30
12.06	2.12	8.31	1.50	4.41	1.30		-
12.00	2.05	8.22	1.78	4.35	2.05	-	-

*Fifteen seconds per interval.

initially was drilled in 1976 until alpha activity was encountered; then the well was backfilled. Samples obtained by deepening the well, especially at the anticipated depth of activity, probably were disturbed and are not representative of the actual level of transuranic activity.

Well 184 was located on the west side of the crib, 3.4 m (11 ft) from the crib bottom. The peak neutron flux measurement agreed with the peak transuranic activity, which occurred at approximately 6.8 m (22 ft), but the distribution was dissimilar. The greater activity closer to the crib, and especially at the bottom of the crib at 6.1 m, influenced the background level.

The results of the passive neutron logging were useful in planning the sectioning of the dual-wall core-barrel. The results also supplemented the laboratory determination of transuranic activity. The limitations of the system, however, made determination of the plutonium and americium distribution dependent upon the laboratory analyses discussed in the "Results" section. The results from the active system are in general agreement with the laboratory data, but additional work is needed to demonstrate that it can provide useful information without support of laboratory analyses.

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